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JULY 1929

THE BY-PASSING AND DISCONTINUOUS DEPOSITION OF SEDIMENTARY MATERIALS[1]

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Los Angeles, California

ABSTRACT

Features of the sediments in various basins observed indicate that more material was supplied to these basins than was finally deposited in them. Under this condition, sedimentation was locally restricted or interrupted at frequent intervals during which most or all of the material received was passed onward. Sedimentation of a sufficiency such that a temporary baselevel of deposition is attained at frequent intervals, is termed adequate.

The view that most sedimentation in epeiric seas and on continental shelves has been closely controlled by a segregative, restrictive, and evening action under the influence of the profile of equilibrium, is supported. It is concluded that the profile of equilibrium controls sedimentation in the neritic environment through the agencies of by-passing and discontinuous deposition, and that an understanding of these agencies is a key to many problems in texture, stratification, lenticularity, and differing thicknesses of sediment at equivalent time horizons. It is further concluded that, where conditions of past adequate sedimentation were present during the laying down of a conformable succession, the absolute and comparative subsidence at a locality can be approximated within permissible error, and various relations between coarse and fine-textured sediment can be explained.

INTRODUCTION

Barrell[3] published his revolutionary theory on certain controls of sedimentation in the year 1917. The theory was presented in a thesis on the measurements of geologic time, and he laid down his pen before

[1]Presented by title at the Los Angeles meeting of the Pacific Section of the Association, October 29, 1927. Manuscript received by the editor, March 12, 1929.

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[3]Joseph Barrell, "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. Amer.*, Vol. 28 (1917), p. 747.

providing the later expansion and development which he only could have given.

The writer lists some evidence and inference in an endeavor partly to recover lost details. The basic theory is put forth in the words of Barrell as a separate short chapter which is segregated not only because of its importance, but also to emphasize that the extensions of theory thereafter presented do not condition the fundamental concept.

Statement of the basic theory is followed by an extension of theory, and this in turn by further amplification looking toward the construction of various working hypotheses. Two districts that have provided some of the data on which the theoretical considerations have been based are then briefly described.

NOMENCLATURE

Several terms used in the present paper, some old and some presumably new, are here defined.

By-passing[1] occurs when one particle of sedimentary material passes another particle simultaneously transported, or continues in motion beyond the point at which such other particle comes to rest. It occurs in the transportation by water of particles differing in size, density, or shape, and is illustrated by an areal gradation in the texture of nearly all terrigenous sediment.

Discontinuous deposition is discussed from the standpoint of recurring intervals during which there is locally an absence of sedimentation due to total passing. Such intervals occur when all relevant profiles of equilibrium drop to or below the surface of the lithosphere. (For most purposes we may disregard replacement and substitute *the* profile of equilibrium.) They occasion innumerable breaks in deposition in the neritic environment, that is, diastems.

The profile of equilibrium is a horizon (above, at, or below the surface of the lithosphere) at which, if and when attained, deposition and erosion are balanced for the existing conditions.[2] Sea bottoms above the

[1]*Geol.* In the sense of inverting the term "passing by." Shortened nomenclature for a well-known phenomenon. In the present paper: (1) *by-passing* designates a relation between particles transported in a given time or phase, (2) *total passing* refers to a local relation between particles transported in a given time or phase and stationary particles of a preceding time or phase.

[2]The feature that gravel can be deposited at the same time and place that sand or clay is being scoured, shows that there is simultaneously a different profile of equilibrium and potential baselevel of deposition for every size, density, or shape of particle. *The* profile of equilibrium for the existing conditions is the net result of a great many simultaneous profiles. The simultaneously different horizons assumed by contemporaneous profiles, some above and some below sea bottom, allows by-passing to take place. Replacement can take place at *the* profile, but when *all relevant* profiles recede below sea bottom at a locality, even this phase of sedimentation is precluded. In the present paper, "the" profile refers to a net result, except when a particular kind of particle is being discussed.

profile of equilibrium are subject to scour, those below the profile are subject to sedimentation. The term discussed has frequently been used by authors to designate the average horizon assumed throughout a length of time, without regard for temporary fluctuations above and below such an average. This broad usage is at times convenient, but for present purposes a finer discrimination is advisable.

A temporary baselevel of deposition is attained at a locality when the profile of equilibrium for the existing conditions drops to or below the sea bottom or other analogous surface. Net sedimentation then ceases until the profile of equilibrium rises above the bottom.

Adequate sedimentation is a term proposed to designate sedimentation which results, at short intervals, in the attainment of a temporary baselevel of deposition. Adequate sedimentation may take place, under favorable conditions, in all parts of an epeiric sea or embayment which receives plentiful material and has adequate currents, in parts of these which are adjacent to a source of material, or on parts of a continental shelf where sufficient material is received and spread. Inadequate sedimentation is the reverse of the foregoing. It may take place in certain subsiding areas distant from a shore line, and in parts of other areas nearer land which receive an insufficient amount of material.

Adequate currents is a term applied herein to currents in a body of standing water which are capable of handling, and therefore of spreading to a reasonable degree, received materials. The word currents, when unqualified, is used throughout this paper to include currents proper, tides, and waves. Inadequate currents are the reverse of those designated as adequate.

Deltaic accumulation is that in or on a delta. A delta has been defined by Barrell[1] as "a deposit partly subaerial built by a river into or against a body of permanent water." Twenhofel[2] states that "a delta results from a stream supplying more material than can be handled by the waves and currents of the body of water into which it empties." There seems to be no general agreement as to where a delta ends. The present writer herein considers a delta to end where the submarine cone or other characteristic shape is terminated by the action of adequate currents.

Disseminated accumulation is a term used in the present paper under which to group all accumulation which is dominated by adequate

[1]Joseph Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Amer.*, Vol. 23 (1912), p. 381.

[2]W. H. Twenhofel, *Treatise on Sedimentation*, Williams & Wilkins Co., Baltimore (1926), p. 590.

currents in standing water; therefore, it is not deltaic. The necessary materials may be furnished by the discharge of rivers, wave action on coasts, scouring and re-working of bottoms, by organic remains, and other sources and agencies. Disseminated accumulation is indicated to have furnished the bulk of the marine sediments laid down in geologic time.

Unconformities, in a restricted sense, are considered to involve emergence. They may be both angular and erosional, or merely erosional. A disconformity is regarded as being a variety of unconformity which reveals neither perceptible angular discordance nor erosion between underlying and overlying formations. A diastem is viewed, following Barrell, as being a break in sedimentation due to shorter or longer downward oscillation of wave-base, that is, as involving an interval during which there is no permanent sedimentation in parts of a body of water (for practical purposes, no appreciable sedimentation).

Epeirogeny is regarded as embracing the more regional aspects of diastrophism, with emphasis on a more or less direct elevation and subsidence; orogeny, as embracing the more local expressions of diastrophism such as folding and related deformation. There is no sharp line, in practice, between epeirogeny and orogeny. Both expressions of diastrophism are found together, and the geologist can at best only call attention to a preponderance of one in a particular case. Epeirogeny is here viewed as being the more primary and regional expression, orogeny as a more secondary and local feature commonly developed as a product or partial relief of pressure along zones of contact or weakness.

A revolution is thought of as being a time of increased departure upward from an average for earth conditions, this ordinarily involving slowly increased diastrophism, but conceivably due to solar or other variation which may affect climates and life without material diastrophic change.

I. Basic Theory

Factors in sedimentation which control deposition in the neritic and related environments were recognized by Barrell[1] as follows:

> ....The deposition of nearly all sediments occurs just below the local baselevel, represented by wave base or river flood level, and is dependent on upward oscillations of baselevel or downward oscillations of the bottom, either of which makes room for sediments below baselevel. According to this control, the rate of vertical thickening is something less than the rate of supply, and the balance is carried farther by the agents of transportation. The storage of the

[1] Joseph Barrell, "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. Amer.*, Vol. 28 (1917), p. 747.

final excess, except for locally deep water on the lands, is on the abyssal slopes of the continental platforms, constituting deposits lost to observation, since it is a region which has been seldom uplifted and exposed by erosion.....

The deposition of a series of beds where the material is carried along the bottom by stirring of currents or oscillations of waves is ordinarily not a continuous process, even during a stage of crustal depression, but represents an irregularly rhythmic alternation of fill and scour with a balance in favor of the fill. There are minor time blanks, consequently, in what appears to be a continuous succession of beds, and larger and larger intervals separate the larger and larger divisions of a series.

II. Extension of Theory

Details have been observed or inferred by the present writer as follows.

Variation in the profile of equilibrium.—The horizon of the profile of equilibrium (baselevel) is extremely variable in the neritic environment, according to the strength and direction of currents, the kind and amount of available particles, or a combination of these features. The average horizon throughout a long period is determined in large part by rates of subsidence or elevation of the sea bottom and by cycles of erosion on the land, but the innumerable fluctuations which occur during such a period are deemed to be chiefly a result of variations in current modified by minor variations in the amount and texture of available materials. Variation in the horizon of the profile of equilibrium appears to be normally a function of its curve. Both the curve and the amount of vertical variation are commonly largest near shore, decrease basinward in deeper waters, and reach a theoretical zero in distant or quiet waters where the cause does not operate.

All water-spread sediments must be laid down below the highest horizon assumed by profiles of equilibrium. Sediments laid down on upward fluctuations of the profile will be temporary if the profile falls on subsequent downward fluctuations low enough to allow currents to overcome the inertia, adhesion, or other property of the particles deposited. They will become permanent if the inertia, adhesion, or other property of the particles is sufficient to hold them in place during downward fluctuations until safely buried by later sediment.

Temporary baselevels of deposition.—Temporary baselevels of deposition are in the aggregate related to rates of subsidence and to long cycles in erosion on the land, but any single level is considered to be chiefly the result of a transient relation between current strength and the amount and kind of available material.

The horizon at which a temporary baselevel of deposition is attained at a particular locality, and its areal expansion and contraction, are dependent on complex and variable combinations the effect of which may be the opposite of what one might expect from considering one factor. An increase in current strength may either raise or lower the horizon at which a temporary baselevel of deposition will be attained at a locality, or may either extend or contract an attained horizon areally, depending on the amount and kind of available particles. In this connection, and throughout the further discussion, it should be kept in mind that particles available by reason of shifting temporary deposits are probably at nearly all times more numerous in the neritic environment than are the primary accessions from rivers or from other land sources.

Scour and fill.—The arrival, retention, or departure of particles touching a given part of the sea bottom is determined by their particular resistance to currents. Unconsolidated clay particles are more easily moved than sand, and sand than pebbles.

Assuming a temporary baselevel of deposition to have been attained on a clay bottom, a certain increase in current strength may scour the clay and (bring and) deposit gravel of a certain size or other property at the same time or place, for the reason that the simultaneous profiles of equilibrium and baselevels of deposition for clay and for pebble particles are simultaneously different as to horizon. (1) If clay is removed in greater bulk than the particular gravel arrives and is screened out, the sea bottom will be lowered. (2) If the erosion of clay and arrival of gravel are equal in bulk, the bottom will be neither raised nor lowered during such time as the clay is exposed. (3) If the gravel which is brought and deposited is greater in bulk than the clay which is scoured, the bottom will be raised.

Again, assuming a temporary baselevel of deposition to have been attained in gravel in accordance with a particular current strength and available material, if current strength is then decreased so as to form a new combination with sand of a particular quality as the material to be (brought and) screened out at this locality: (1) if sand of the particular quality arrives, the bottom will be built higher; (2) if no sand of the particular quality arrives, the gravel bottom will maintain its level. It can not degrade because its pebbles have an inertia which overbalances the power of a current which drops sand, and it can not aggrade because the current adjusted to drop sand of a particular quality (*a*) fails to bring such sand, (*b*) can not bring particles coarser than such sand, and (*c*) sweeps all particles finer than such sand beyond the locality.

Whenever current increases at a locality to a strength greater than the resistance of all available particles, a status quo or scouring must result at that locality even though large amounts of material are furnished and transported. If current strength fails entirely, there can be no aggradation through traction, but aggradation may for a time take place through a settling of fine particles from suspension or solution.

When a large number of localities is considered simultaneously, relations are further complicated by the feature that the profile of equilibrium is raised or lowered unequally in different parts of a district due to its curve being more variable than the curve of sea bottom. Given a combination causing strandward scour and basinward fill, a change in current strength may reverse this relation and cause strandward fill and basinward scour.

It seems certain that comparatively little permanent sediment of the neritic environment is laid down directly from new materials, but that most of such sediment represents the ultimate position of particles laid down first as temporary deposits and shifted back and forth perhaps many times to many positions. Various parts of a neritic bottom thus take turns in being storehouses for one another. This feature allows a particular part of the sea bottom to accumulate sediment rapidly for a short time, after which it may receive practically no permanent deposits or may be scoured for a long succeeding period during which the received and shifted materials of a basin will come to rest on other parts of the bottom.

Considering all parts of a neritic environment at the same time, local fill and scour are extremely complex matters which involve an almost infinite number of possible combinations between current strength and direction, amount and kind of available materials, and, as regards scouring, the resistance of different parts of the sea bottom to submarine denudation. It is obvious that minor fill and scour are determined almost entirely by fluctuations in the profile of equilibrium which are due to varying current and load throughout rather short periods, and that only an aggregate of permanent fills is dominated by subsidence. Wherefrom: (1) *an individual fill, either permanent or temporary, may occur without any paralleling subsidence of the sea bottom;* (2) *pebbles or sand may be deposited above clay, or vice versa, without any preparatory change in the depth of water.* Moreover, an individual baselevel of deposition must ordinarily be of fleeting duration, and is not to be confused with either the age-long baseleveling of land areas, or the ultimate average baselevel of those sea bottoms which do not undergo net sedimentation.

The foregoing becomes clearer when we remember that, though subsidence perhaps seldom exceeds ½ inch in a year's time, the range in horizon of the profile of equilibrium may be many feet during the same period, and changes in off-shore current can alternately raise and lower the profile considerable distances in cycles each covering a number of years. The writer would emphasize the long-term or average control of the profile of equilibrium by subsidence, and the comparative freedom of individual fluctuations of the profile from such control.

The storm horizon of the profile of equilibrium probably controls the shape of sea bottom and the depth of water in areas of adequate sedimentation, for the deep and powerful action of great storms should periodically equalize areal differences in the amount of aggradation. Sediment laid down during such storms would tend to persist in part, by reason of inertia, through the agitation of lesser storms and quieter times. As available materials are normally less in aggregate bulk seaward, succeeding great storms may there again equalize the bottom before sediment can be built to the comparatively high horizons assumed by the profile of equilibrium in quiet periods. Periodic adjustment in the neritic environment is evidenced by the occurrence of eroded bedding planes. A pebble layer spread during one great storm may be succeeded by sand, and this perhaps by clay, until another great storm scours the fine upper layer, and, depositing coarser material upon the eroded surface, begins another cycle.

Sorting.—A traction-laid particle, and any finer-grained matrix in which it is embedded, are considered to have necessarily been laid down at different times, for reasons which will be obvious. The disparity in age between a large boulder and some of the sand grains adjacent to it on the same plane may be several hundred years. The average disparity in age between particle and matrix is theoretically less where the average texture of the sediments is finer. In basinward "shaly sands" this age disparity may be years, or merely the difference between storm and lull.

The extreme turbulence caused by storms and even normal waves in shallow water there gives rise to exceptionally frequent scour and fill, with resultant mixtures, eroded bedding planes, and lenticularity. A sorting of the particles which come to rest at a locality at any one time, therefore under one combination, must commonly be fairly well defined, but incessant wave action, or change in current proper, ofttimes scrambles the successive layers or particles and precludes visible bedding through relatively long periods of time and considerable thicknesses of sediment.

Good or poor sorting and bedding in an ultimate product seems to be closely related to what might be termed the "frequency" of current, that is, the times and amounts of variation in current strength and direction. A current, whether strong or weak, can never lack the *power* of sorting what it brings. Traction-laid sediment which is now poorly sorted must nearly always represent a large number of good primary sortings which have been scrambled. A piece of traction-laid conglomerate which contains a hundred distinctly different kinds of grain as regards mass or an equivalent property, normally represents a hundred different times and conditions of deposition, and may also represent a hundred thin layers of well-stratified appearance farther basinward. Primary sorting of neritic sediment is accomplished by means of by-passing. Mixtures and bedding planes in such sediment commonly, but not necessarily, include discontinuous deposition.

Rates of accumulation.—Accumulation of sediment in the neritic environment is closely controlled by features of by-passing and of discontinuous deposition. Variation in the position of the profile of equilibrium above sea bottom affects the degree and uniformity of by-passing. Temporary recession of the profile to or below sea bottom causes total passing, with resultant minor interruptions in deposition (diastems). When the profile of equilibrium is approached at any point during deposition, fewer particles are deposited at that point, and more particles by-pass these and continue beyond. When the profile of equilibrium is attained at any point, all particles of transported material pass this point and are swept to points where the profile of equilibrium has not been attained (disregarding replacement).

Temporarily unequal rates of accumulation are leveled, in the neritic environment, by means of the average horizon of the profile of equilibrium. Strandward areas which tend to build up rapidly undergo comparatively short periods of permanent sedimentation and suffer long periods of total passing or of scour. Basinward areas which tend to build up more slowly have longer periods of permanent sedimentation and suffer shorter periods of total passing or of scour. The product is in both cases subject to an evening action of the great storms which determine times of maximum equalization.

Time represented by equivalent appreciable thicknesses of boulder beds compared with clay beds in an area of adequate sedimentation probably does not differ materially along the same contour of subsidence, for the thicknesses of the ultimate product are equalized by diastems and by differing degrees of by-passing. *Time of deposition* may vary in the ex-

treme, the ratio of appreciable sedimentation, on comparison of certain clay and boulder beds in Ventura Basin, having possibly been as high as 1,000 to 1.

For example, if a 1-foot average of permanent sedimentation is assumed to take place in a district in a total of 50 years, this vertical thickness might be represented by the deposition of a boulder a foot in diameter, by several hundred sand grains resting one upon another, or by many thousand clay particles. Near a source of materials, a very exceptional storm might well deliver, or concentrate by shifting, a foot of boulders near the mouth of a stream (their mass would commonly hold them above the average horizon of the profile of equilibrium during lesser storms), thus attaining a temporary baselevel of deposition in a few days and there might be no appreciable addition of permanent sediment at this locality for perhaps 50 years thereafter except for a sifting into interstices. A little farther basinward, the exceptional storm would normally be represented by a thin pebble or sand layer spread over a wider area, and the balance of the 50-year period by several thin layers of sand or pebbles each representing a short period of storm deposition separated by several years of temporary fill and of scour without permanent accumulation. Still farther basinward, where only small quantities of rather fine material arrive or are shifted at any time, the foot of sediments might be composed in part of very thin layers of storm sand laid down at intervals, these being separated by clay layers representing a slow settling and partial retaining of fine particles during a part of the time intervening between the periods of deposition of the sand layers. The thin layers as a whole might be re-worked into a massive "clayey sand."

The foot of boulders could be deposited entirely (except for a sifting into interstices) during $1/50$ of 1 per cent (1:5000), the same foot of thin pebbly sands and sands during 1 per cent (1:100), and the thin layers of sand and clay aggregating 1 foot during 20 per cent (1:5) of the 50-year period. Time represented would be nearly the same for the foot of sediment regardless of texture or bedding. Time of deposition would be very different. (Time represented equals time of permanent deposition plus time of no permanent deposition.)

IDEAL ILLUSTRATION

An attempt will be made to approximate the principal events and relations during the deposition of an average cycle between two exceptional storms of equalization, assuming, for simplicity, that the subsidence is areally equal. Such an illustration is not to be taken literally,

(1) because no horizon representing a minor cycle can be traced throughout a wide area in any basin examined by the writer, due to the inevitable neritic lenticularity, and (2) because it is doubtful if thin strata persist very far areally in any neritic environment (except on its outer edge), due to areal variation in the profile of equilibrium. A time of strandward aggradation may well be one of basinward scour, and a time of basinward fill one of scouring near a strand, for the horizon of the profile of equilibrium seems to have pivotal axes during certain times.

1. We may first consider the comparatively quiet close of a minor cycle, before equalization. During this quiet time and previously, parts of the bottom normally are cut down below, and parts are built above, the baselevel of great storms.

2. An exceptional storm starts a new minor cycle. The wave action of this great storm extends deeper than previous actions, and by scouring here and building there, it molds the sea bottom to storm base through the agency of a temporary but very active horizon of the profile of equilibrium.

Comparatively large quantities of both fine- and coarse-grained material are received during this storm phase, for the streams are in flood. Many of the coarser particles are retained near shore, some to be later scoured and shifted in part. The fine-grained particles received from the land or originating in shifts are kept rather continuously in suspension, and may be carried far to sea. They subsequently settle, but all particles coming permanently to rest in this time of storm are traction-laid except as regards distant deep waters below wave-base.

The traction-laid sediment comes to rest according to a screen established by simultaneous profiles of equilibrium, each profile being representative of a particular size or kind of particle. The mesh of the screen varies areally with areal differences in current strength, each particle being sorted out and coming to rest in accordance with its mass or other property. At such times and during such periods as strength of current prevents any available particle from coming to rest at a locality, a temporary baselevel of deposition becomes operative, total passing takes place, and a diastem results. The diastem may be of short duration, or, considering that scouring may remove the sediment of a hundred years, it may be rather long. (Diastems viewed in the field will for practical purposes include the time represented by scour.)

3. Next in this ideal cycle comes a succeeding phase of lesser storm and of lull. Smaller amounts of material are received or shifted, and these contain few large boulders, although cobbles and pebbles are de-

treme, the ratio of appreciable sedimentation, on comparison of certain clay and boulder beds in Ventura Basin, having possibly been as high as 1,000 to 1.

For example, if a 1-foot average of permanent sedimentation is assumed to take place in a district in a total of 50 years, this vertical thickness might be represented by the deposition of a boulder a foot in diameter, by several hundred sand grains resting one upon another, or by many thousand clay particles. Near a source of materials, a very exceptional storm might well deliver, or concentrate by shifting, a foot of boulders near the mouth of a stream (their mass would commonly hold them above the average horizon of the profile of equilibrium during lesser storms), thus attaining a temporary baselevel of deposition in a few days and there might be no appreciable addition of permanent sediment at this locality for perhaps 50 years thereafter except for a sifting into interstices. A little farther basinward, the exceptional storm would normally be represented by a thin pebble or sand layer spread over a wider area, and the balance of the 50-year period by several thin layers of sand or pebbles each representing a short period of storm deposition separated by several years of temporary fill and of scour without permanent accumulation. Still farther basinward, where only small quantities of rather fine material arrive or are shifted at any time, the foot of sediments might be composed in part of very thin layers of storm sand laid down at intervals, these being separated by clay layers representing a slow settling and partial retaining of fine particles during a part of the time intervening between the periods of deposition of the sand layers. The thin layers as a whole might be re-worked into a massive "clayey sand."

The foot of boulders could be deposited entirely (except for a sifting into interstices) during $^1/_{50}$ of 1 per cent (1:5000), the same foot of thin pebbly sands and sands during 1 per cent (1:100), and the thin layers of sand and clay aggregating 1 foot during 20 per cent (1:5) of the 50-year period. Time represented would be nearly the same for the foot of sediment regardless of texture or bedding. Time of deposition would be very different. (Time represented equals time of permanent deposition plus time of no permanent deposition.)

IDEAL ILLUSTRATION

An attempt will be made to approximate the principal events and relations during the deposition of an average cycle between two exceptional storms of equalization, assuming, for simplicity, that the subsidence is areally equal. Such an illustration is not to be taken literally,

(1) because no horizon representing a minor cycle can be traced throughout a wide area in any basin examined by the writer, due to the inevitable neritic lenticularity, and (2) because it is doubtful if thin strata persist very far areally in any neritic environment (except on its outer edge), due to areal variation in the profile of equilibrium. A time of strandward aggradation may well be one of basinward scour, and a time of basinward fill one of scouring near a strand, for the horizon of the profile of equilibrium seems to have pivotal axes during certain times.

1. We may first consider the comparatively quiet close of a minor cycle, before equalization. During this quiet time and previously, parts of the bottom normally are cut down below, and parts are built above, the baselevel of great storms.

2. An exceptional storm starts a new minor cycle. The wave action of this great storm extends deeper than previous actions, and by scouring here and building there, it molds the sea bottom to storm base through the agency of a temporary but very active horizon of the profile of equilibrium.

Comparatively large quantities of both fine- and coarse-grained material are received during this storm phase, for the streams are in flood. Many of the coarser particles are retained near shore, some to be later scoured and shifted in part. The fine-grained particles received from the land or originating in shifts are kept rather continuously in suspension, and may be carried far to sea. They subsequently settle, but all particles coming permanently to rest in this time of storm are traction-laid except as regards distant deep waters below wave-base.

The traction-laid sediment comes to rest according to a screen established by simultaneous profiles of equilibrium, each profile being representative of a particular size or kind of particle. The mesh of the screen varies areally with areal differences in current strength, each particle being sorted out and coming to rest in accordance with its mass or other property. At such times and during such periods as strength of current prevents any available particle from coming to rest at a locality, a temporary baselevel of deposition becomes operative, total passing takes place, and a diastem results. The diastem may be of short duration, or, considering that scouring may remove the sediment of a hundred years, it may be rather long. (Diastems viewed in the field will for practical purposes include the time represented by scour.)

3. Next in this ideal cycle comes a succeeding phase of lesser storm and of lull. Smaller amounts of material are received or shifted, and these contain few large boulders, although cobbles and pebbles are de-

livered by streams in minor flood or are rearranged as to position. The strand is slowly cut down and its boulders isolated, for, while the minor storms of this phase shift some material strandward, their wave-action is less powerful than that of the preceding great storm, and the waves of still quieter times will cut down the oversteepened shore. The minor storms may shift cobbles a certain distance along the strand, and drop them among boulders in shallow water, thus starting a matrix.

Particles deposited from suspension during this moderate phase can come to rest nearer shore than during the previous time of great storm. The result is that layers of the cycle tend to average a finer texture upward. Clay lenticles extend closer to the strand, but can not be permanent very far in this direction due to the intermittent minor storms. By-passing and discontinuous deposition are operative as before, but the average mesh of the screen at a locality, and the average locale of diastems are somewhat different.

4. There comes a closing and more quiet phase of the cycle. The same tendencies are operative, but the materials furnished by streams or shifted have pebbles as the largest particles furnished in quantity. The strand is further cut down. The matrix for certain shallow-water conglomerates is completed by a sifting of pebbles and sand into interstices, for the scouring action around boulders is diminished. Clay layers can extend still nearer shore than formerly, and such layers laid down rather far strandward may persist in part through light storms of this phase and their eroded remnants be known from small lenses in or between conglomerates, or from clay pebbles. In outer areas, the sand grains arriving during any period of time may be insufficient in quantity to form distinct layers, and may settle to form paper-thin laminations which are gently re-worked by the whisper of light storms on the surface and incorporated with overlying or underlying clay laminations to form a "clayey sand" of homogeneous appearance.

Another exceptional storm will eventually follow this last phase, will again equalize the sea bottom, and will start another minor cycle. A cycle such as the one outlined need not progress so evenly and simply from bottom to top, or have any particular thickness, or even be traceable in sediment due to scour and lenticularity. A nearly rhythmic aspect is nevertheless commonly apparent much as described.

Complex variations.—Sedimentation in the neritic environment is modified by factors of such complexity that a lifetime of study would be necessary to untangle and explain the details of even a few of them. A key to many problems is believed to be an understanding of the various

elevations *and curves* assumed by the profile of equilibrium under different kinds, strengths, and directions of current. Variations of the profile in a marine area are extremely numerous and pronounced. There may be a vertical range of several feet between storm and lull, and a sudden change from persistent gravel to persistent sand deposition seems scarcely explainable except by a change in off-shore current such as might involve possibly from 10 to 100 feet of vertical change in the horizon of the profile of equilibrium.

In an area of adequate sedimentation, the sea bottom is almost continuously built up to, or near, the average horizon of the profile of equilibrium. If the sea bottom subsides at the rate of 1 inch in 4 years, then 1 inch of room is provided for permanent sediments during this time. Where deposition has, for 4 years, a 1-inch average margin to work on, there must be some interesting relations between sedimentation and storms or stormy seasons which cause the elevation and curve of the profile to vary many feet in this time, and to have many intermediate gradations.

Moreover, cyclic variations in the strength and direction of off-shore currents may cause total passing to be rather persistent locally for a number of years, or may occasion especially rapid local deposition for a time. Alternating thick layers of gravel and of clay are evidence that some such factors were at work. Under such circumstances the particles of a different size or other quality were laid down elsewhere.

III. Further Amplification of Theory to Form Working Hypotheses

The basic features by-passing and discontinuous deposition need not be made the subject of theses, for the first of these features is one of the oldest tenets of the science of sedimentation, and the second has been on a firm foundation since Barrell published his classic paper.

However, so little is known as yet about the detailed action of the features in distributing and controlling sediments, that some of the most common results to which they give rise offer an almost virgin field for investigation. A framework in this field has been sketched in previous pages. The writer will now amplify and rearrange the theory in order to apply it more directly to the solution of certain problems.

INFERRED LAW

1. The thickness of permanent sediment deposited in a sea between the attaining of any two temporary baselevels of deposition is equal to

the amount of subsidence, plus or minus the difference in sea level and in the horizon of the profile of equilibrium at the two baselevels.[1] Reversed:

2. The amount of subsidence of a sea bottom between the attaining of any two temporary baselevels of deposition is equal to the thickness of permanent sediment deposited, plus or minus the difference in sea level and in the horizon of the profile of equilibrium at the two baselevels.

3. The thickness of permanent marine sediment deposited at different points on the same contour of subsidence between the attaining of any two temporary baselevels of deposition common to these points, is the same, plus or minus the compared difference in the local horizons of the profile of equilibrium at the two baselevels (regardless of areal differences in texture or bedding).

WORKING HYPOTHESES

In waters having current, the profile of equilibrium controls deposition, and limits the height to which sediments can be built and the depth to which they can be scoured. Control and limitation are exercised through the agencies of by-passing, discontinuous deposition, and scour. The more important determining factors are:

A. Currents, involving mechanics of distribution.

B. Rate of subsidence or elevation, involving the vertical factor in capacity.

C. Transgression or regression, involving the areal factor in capacity and the question of proximity.

D. Times of erosion on the land, involving the kind or amount of primary particles.

The factors are listed in what is believed to be their average order as regards short- to long-term control of sedimentation. Some modify the others. For example, change in the factor *B* is in some instances paralleled more or less closely by *C*, sometimes influences *D*, and may affect *A*, but not necessarily. For example, a trough may fold downward with increasing rapidity and encroaching flanks at the same time cause regression, thus reversing the ordinary relation between *B* and *C*.

The present paper is not concerned with the abyssal waters of the earth, but rather with the prevailingly neritic waters of the continental

[1] The thickness refers to that at the time the upper baselevel of deposition is attained. Contemporaneous compaction or other distortion therefore does not apply. When computing absolute past subsidence from present thicknesses, subsequent compaction or other distortion should be computed and allowed for.

segments. A neritic environment implies adequate sedimentation, and this, in turn, by-passing and discontinuous deposition. Prevalence of these four features during the laying down of a succession is evidenced by persistent thicknesses of traction-laid sediment, persistent alternation of such sediment with that deposited from suspension or solution, or a frequent occurrence of diastems in sediment of any texture. A possible presence or dominance of the features in massive deposits of limestone, clay, or other fine-grained sediment may ordinarily be difficult to ascertain. A combination of powder-fine particles and almost imperceptible current in basinward portions of a shallow sea may cause the features to be as persistent there as in coarse-grained sediment near a strand. Such a combination will, however, in many instances be conjectural and difficult to distinguish in ancient sediment from a more or less direct settling of particles to deep and quiet bottoms.

DIASTEMS

The more easily recognized diastems, which involve pronounced lensing, eroded bedding planes, or gravel on clay, are not necessarily the longest, and certainly they are not the most frequent. Similarity in texture and other quality of the particles deposited before and after a long diastem may hide its presence, for the particles above tend to be deposited around, or re-worked into, those below. Discontinuity will be particularly difficult to determine in basinward parts of a broad and flat-bottomed epeiric sea where off-shore currents move in one direction at rather uniform strength for long periods of time.

A change in the degree of by-passing can give rise to certain features similar to those resulting from diastems (and in its extreme stages by-passing merges into total passing), but the commonly great number of fluctuations in the horizon of the profile of equilibrium suggests that a diastem exists at almost every perceptible change vertically in the texture of traction-laid sediment.

The occurrence of diastems which involve no perceptible stratification is indicated by the presence of impure traction-laid sediment in conglomerates, and in some shaly sands and sandy shales. It will be obvious that a thick and massive bed of conglomerate containing scrambled particles which differ markedly in size commonly only represents many different times and phases of deposition which are separated by diastems. And yet it is difficult for the geologist to put his finger on more than a very few, if any, of the breaks. Those sediments differing in grain called pebbly sands, shaly sands, and sandy shales, are, strictly speaking,

also conglomerates. The presence of an indistinct line of pebbles in clay or sand has in some places been the only evidence of discontinuity observed by the writer in fine-grained marine sediment theoretically containing numerous diastems.

The writer considers a diastem to be indicated at nearly every sharp change upward to sediment of coarser grain. Less strongly, at a sharp change upward to sediment of finer grain. A coarse-textured stratum commonly rests upon one of finer grain with a comparatively clean contact, which is suggestive of a hiatus. A fine-textured stratum commonly rests upon one of coarser grain with a somewhat more gradational aspect which may or may not represent a diastem hidden by re-working or infiltration. Stratification even between thin strata may involve a diastem from a season to perhaps many years in length. Shorter and more numerous diastems are believed to be represented by certain changes in grain within a stratum which do not result in perceptible stratification.

Diastems involving heavy scour, or coarse sediment on fine, may be very apparent. There is the paradox that many such diastems are more visible than unconformities of emergence which involve a hiatus represented elsewhere by several thousand feet of sediments. This phenomenon is perhaps due in part to the feature that the waves of a transgressing sea tend to re-work and smooth the surface it advances upon, whereas the more prominent diastems are ofttimes due to sudden change in off-shore current which occasions locally deep scour and follows this by dropping particles markedly different in grain from those of the preceding phase.

Diastems are normally longest and correspondingly of least number on strandward bottoms due to proximity to material, rapid attainment of temporary baselevels of deposition, and a removal of temporary sediment by deep scour. They are normally shorter and correspondingly more numerous in the finished product on basinward bottoms where the conditions of deposition are in a sense reversed. A diastem may represent a tide, or, considering sediment removed by major scour, many thousand years. (In its broadest definition, a diastem is any hiatus which does not involve emergence.)

The percentage of aggregate time represented by diastems compared with aggregate time of permanent sedimentation is extremely vague, particularly as this changes areally, and in no two basins or parts of basins is the same. In the Fernando group sediments of Ventura Basin, diastems can hardly aggregate less than 99 per cent of the time represented in certain far-strandward areas, but may possibly aggregate as little as

50 per cent of the time represented in the most basinward areas whose strata are exposed.

TEXTURE

Of individual strata at a locality.—Vertical alternation of coarse and fine-textured sediment at a locality is considered to be due chiefly to variation in the strength and direction of currents, where less than a member of a formation is dealt with. In dealing with alternating thin layers of gravel, sand, and clay assumed to represent 50 years each, it is obvious that the rivers or other agents did not deliver pebble, sand, or clay particles only, for 50 years at a time. Nor did the sea bottom oscillate up and down as rapidly as this, or the waters transgress and regress materially after such short intervals.

The materials delivered to a sea will seldom be spread immediately over the entire bottom, but will probably be shifted at different times, under different conditions, and in different amounts, to various parts of the sea floor. This is shown by the feature that an area of adequate sedimentation which shows an ultimate rather even distribution of material as regards quantity, has strata which lens out and disappear with distance and are overlapped or replaced by other lenticular layers.

Rapid alternation of gravel, sand, and clay layers at a point necessitates a rapid change in the horizon of the profile of equilibrium. This alternation must commonly result from variation in the strength and direction of currents, and be more or less independent of long-range factors. Such variation causes particles stored near a source of materials or elsewhere to be shifted, at different times and in different amounts, to other localities. A current may drop gravel at a point, weaken and lay down a sand stratum, and later, regaining strength, either again deposit gravel, or remove the sand. When shifting material, a current of a certain strength will pick up and carry clay particles only; a stronger current, both sand and clay; and one still stronger, pebbles, sand, and clay. However, while a current of a certain strength can move many of the textures mentioned, it can drop a particle of only one texture at a particular locality. It follows that an alternate waxing and waning in current strength will tend to deposit alternate layers of coarser- and finer-textured particles which will more or less successfully resist scouring, and that the origin, destruction, or survival of the individual layers at a locality is directly dependent on current strengths and is only indirectly related to long-range factors which will be mentioned later.

As conditions favoring deposition at one locality are commonly unfavorable for deposition at some other, sedimentation at one point in a

basin will normally be represented at other points in the basin by an absence of sedimentation or perhaps by scour. This feature tends toward alternation of textures in a vertical direction, and would cause such alternation even though the amount and texture of the various materials entering a basin should remain constant. It prevents any monotonous grading and continuity of permanent sediments from the strand or other source of materials outward. It obviates the necessity of an individual stratum grading through a complete cycle from boulders to clay in a basinward direction, but rather permits clay, sand, and pebble particles to be segregated into more or less separate lenses. Weak currents will shift only the finer particles, and will thus contribute toward separating them into a lens. The coarse and fine particles moved simultaneously by a strong current may be laid down as an areally graded deposit, but subsequent scouring may purify this deposit to the extent of leaving a lens composed almost entirely of the coarser particles.

It is thus unnecessary for a stratum which is locally of medium texture to become coarse- or fine-grained in a lateral direction, for it may lens out and disappear before changing its texture materially. However, as all other textures furnished to the basin must, disregarding wear, be represented by sediment somewhere, in such a situation these other particles will be incorporated in other lenses. The shifting of materials, first laid down as a sheet deposit graded areally to form one fairly complete textural range, makes it possible by the partial removal of contained textures at different times and under different strengths of current, for pebble, sand, and clay particles furnished by the same tiver flood to come to permanent rest on a sea bottom in layers one above another.

Summarized, the texture of a stratum at any one point and horizon is viewed as being chiefly the result of a temporary horizon of the profile of equilibrium which establishes a temporary mesh of the screen at that locality; therefore, a particular degree of by-passing. As the profile, mesh, and degree change, the texture of the sediment deposited locally changes. In each such shift the particles of a different grain are laid down in another locality, or in the same locality at another time. The variable horizon (particularly curve) of the profile of equilibrium alternately favors different parts of a bssin as regards deposition and scour. This feature tends to cause material heterogeneous in texture, originally furnished by a single river flood, to be shifted from temporary deposits and be spread at different times by different strengths of current to form

lenses, some of which show marked areal gradation in texture, and others of which have particles that are more or less related texturally.

Average local texture.—When the *average* texture at a locality of members or formations of considerable thickness is viewed, other and long-term factors may be dominant.

1. Change in rate of subsidence may be suspected as a possible cause of variation between members. Successive marine terraces and land surfaces show that depression and elevation have not always proceeded at a uniform rate. Crustal oscillations involving reversal are confined chiefly to divisions of at least formational rank. On the other hand, rhythmic change in rate of subsidence or elevation seems to have been operative at nearly all geologic times. Reversals are thus suggested by unconformities of emergence, and hesitations in rate of subsidence or elevation by successive terraces, land surfaces, or by alternation of thick coarse- and fine-textured members in a formation.

Variation in rate of subsidence is commonly reflected locally in the average texture of a succession, because it changes what is here termed the vertical factor in the capacity of a basin. Given a persistent quantity and variety of received materials resulting in medium-textured sediment at a particular locality undergoing adequate sedimentation and having a certain range in current strength and direction, a decrease by half in the rate of subsidence would normally coarsen the average texture of sediments to be laid down at that locality. Reduction in capacity with the same intake of material tends to concentrate the coarser particles and to pass more of the finer ones onward. Increase in rate of subsidence would reverse the result. Change in rate of subsidence may be suspected where the average texture in a conformable succession alternates in considerable thicknesses, particularly where the extent of the sea, the rate of land erosion, and the dominant current are indicated to have remained fairly constant.

2. Transgression and regression determine what is here termed the areal factor in the capacity of a basin. Given a persistent quantity and variety of received particles, they cause an average finer or coarser texture of local sediment by moving the strand farther from, or nearer to, a particular point, and by changing the size of an area over which neritic sedimentation takes place.

Transgression and regression are not necessarily parallel, or even complementary, to increasing and decreasing rates of subsidence, although a relationship is common. With areally uniform subsidence and with low lands, even a minor depression may occasion widespread trans-

gression. With areally unequal subsidence and with high lands, major depression may take place locally with little accompanying change in the extent of the sea. As previously indicated, where lateral compression or certain kinds of tilting are dominant, deep parts of a trough may subside rapidly and one or both of its sides rise at the same time (Ventura Basin and the Coloradic geosyncline).

3. Different averaged times of erosion on the land due to diastrophic or climatic changes or a combination of these and other factors may affect the average texture of the sediments deposited at a point, and may also affect the average texture of all materials received by, and deposited in, a sea. The capacity of a basin undergoing adequate sedimentation is determined by the vertical factor subsidence in combination with the areal factor transgression or regression. The two factors multiplied and combined with time give (cubic) capacity. For a certain capacity, change in the materials furnished, such as a larger average particle or increased amount of the same ratio of particles, will influence the average texture of the sediments to be laid down at a locality. A coarser average particle or a larger number of particles without change in average grain tend to extend coarse sediment basinward, and a finer average particle or smaller number of particles without change in average grain would reduce the basinward extent of coarse-textured sediment.

Differing averaged times of erosion are considered to be a factor which ordinarily increases in importance with the longer periods. It is probably of minor importance as regards variation in successions of less than formational rank. Climatic changes and not minor variations in climate are being spoken of. A mere wet or dry spell of 10 or 20 years' duration would be hidden in a minor cycle, and local storage followed by subsequent shifting might obliterate any recognizable record of it.

In California as a whole, long-term vertical change in average texture of Miocene sediment at a locality seems to have been due chiefly to variation in rate of subsidence, extent of the sea, and changed erosion on the land, in the order of importance named. In Pliocene time the order was perhaps the same. Perceptible coarsening of average texture at the beginning of the Pleistocene must be ascribed chiefly to increased land erosion accompanying the inception of the Quaternary revolution, for the California seas were in flood. Lateral gradation and textural differences between individual strata were of course due chiefly to variable currents.

Correlative value of texture.—(1) Particular texture has been almost useless to the writer as a means of correlating sediments in separated

localities, for reasons of areal gradation and other features. On the other hand, (2) comparative texture, when applied to thick members of a formation, has been found to be a fairly reliable aid to correlation within an individual basin, and even province. Thus, if in one part of a basin the lower half of a formation is composed predominantly of gravel and the upper half of sand, in another part of this basin the lower half may be composed predominantly of sand and the upper half of shale; that is, although particular texture differs, comparative texture tends to follow a ratio as regards thick members. Nearly all such distinctions die out near a strand, but in compared basinward areas comparative texture has been checked against paleontology,[1] and has been found to be reasonably dependable as an aid to correlation in some basins and provinces.

STRATIFICATION

Stratification of neritic sediment is due almost entirely to diastems and to variation in degree of by-passing, that is, variation in current with resulting change in the profile of equilibrium. Stratification by differing mineralogy and color, as from limonitic layers, foreign additions as a shower of volcanic ash, or change in the amount of organisms, is not uncommon, but such is ordinarily so modified by current as to constitute merely a variation except in deep and very quiet waters.

Most instances of distinct stratification in the neritic environment are believed to involve a diastem. A sharp change in texture implies a longer or shorter absence of local deposition, or a scour, particularly with a change upward to coarser grain. Stratification involving a diastem can be shown, in some places, in a single exposure from a lensing out and disappearance of one or more beds into a bedding plane. Some stratification may result from sharp change in degree of by-passing without there being a cessation of deposition, but because of the ordinarily frequent and large fluctuations in the profile of equilibrium which involve total passing, it is believed that distinct bedding due to change in by-passing alone is comparatively rare, and is confined chiefly to changes upward to finer grain.

Alternation of traction-laid sediment with that settling more directly from suspension is favorable to stratification, and may occasion alternation of thin-bedded layers as between sand and clay. However, if such change in deposition is too frequent to allow the accumulation of distinct layers, or if it involves certain kinds of agitation, an impure mixture such as clayey sand, sandy clay, or conglomerate without dis-

[1]Paul P. Goudkoff and Donald D. Hughes, miscellaneous micropaleontological determinations made for the writer.

tinct bedding planes may result. Stratification will theoretically occur at most frequent intervals in certain localities intermediate in location between the disturbed strand and peaceful deep bottoms, because the most frequent change in deposition from traction-laid sediment to that laid down more directly from suspension occurs there.

The number of bedding planes present in a horizon is commonly not the same in different parts of a basin. When locally massive beds become finer-grained with areal gradation, they commonly acquire bedding planes and sub-beds. Areal change in the number, extent, and duration of diastems, and in the degree of by-passing, causes the single thick horizon of one locality to acquire, in another locality, the additional bedding planes which divide it into many sub-beds which may differ in texture from both a parent bed and from one another. Most thin strata in far-basinward territory probably represent diastems which bound, or are included within, thick beds nearer shore. A massive bed of conglomerate deposited near shore, together with the diastems overlying, underlying, and within it, commonly represents many alternating thin clay, sand, and pebble layers with included small diastems far to basinward.

Stratification is thus not an accurate measure, in most marine sediments, for the rate at which deposits accumulate, or the time represented by a stratum or succession. Geologists working in different parts of the same basin may arrive at different conclusions if they base these on features of bedding. It is dangerous to conclude that a single layer, whether a 100-foot conglomerate, a 1-foot sand, or a $^1/_{10}$-inch clay, represents a year or season. (The marine layers here discussed are not to be confused with the more accurate aqueo-glacial varves, or with the laminating of some salts.)

Alternation of fine- and coarse-textured layers in the neritic environment does not necessarily, or even probably, represent alternate summer and winter deposition. The average neritic layer commonly represents several years if the most probable rate of subsidence is considered. Temporary storage followed by subsequent shifting tends to obliterate seasonal differences, for these have not the significance of the exceptional great storms and quiet phases which occur at irregular times separated perhaps by a great many years. Lakes and dead seas should be viewed separately from the marine environment discussed, for in such there may be a thin and rather regular lamination of deposits due to seasonal banding.

LENTICULARITY

As change in horizon of the profile of equilibrium normally involves changes in its curve which favor one locality at the expense of another

as regards deposition or scour, nearly all thin strata deposited under conditions of adequate sedimentation form lenses which disappear within wider or narrower limits. (The writer is discussing disappearance, not change in texture.)

Lensing-out may be apparent in single exposures, and we may be sure that it is almost universal with distance. It not only occasions areal discontinuity and feathering-out of strata, but probably also a large part of the horizontally irregular grain or laterally intermittent coarse and fine texture observed in some layers. Such layers may seem to be single, but a closer observation will show that the laterally irregular texture of some of them is due to their being composed of many overlapping lenses whose contacts with one another are indistinct or all but invisible.

It seems likely that off-shore currents change their paths in such a manner that one part of a basin may undergo fairly persistent deposition for years while another part receives little sediment or is scoured, the relation being an alternating one. Thus, many feet of sediment in one part of a basin may have little or no expression in another part except in a bedding plane and diastem.

If gravel were being deposited in one part of a basin under the control of an off-shore current maintaining 20 feet of water, a change in direction but not in strength of current might divert the supply of gravel and bring as the coarsest particle sand which can not come permanently to rest until the maximum current strength is considerably reduced. Assuming that 50 feet of water must be attained at this locality before maximum current strength is reduced sufficiently to allow sand deposits to become permanent, a diastem equivalent to 30 feet of subsidence would exist at the contact between gravel and sand. This diastem, represented elsewhere by sediment, could be indistinct because of a gradational contact, for an overlying sand tends to be deposited around the upper pebbles of an underlying gravel. There would at least be a more or less progressive lensing-out of 30 feet of strata between basinward points and the typical locality.

The example given is one of the more extreme and is applicable chiefly when comparing distant parts of basins, but it illustrates the ease with which lesser phenomena of a similar nature may be effected, and the probably limited areal extent of thin layers. Lensing-out makes it impossible to trace the average neritic stratum a foot or so in thickness for any great distance.

Lensing-out is believed to hold the chief key to the relation between parent horizons and their plural offspring. It is thought to have a bear-

FIG. 1.—Moderate lensing in strandward territory. Marine upper Pliocene at Fernando Pass, eastern Ventura Basin. Strata which probably represent a few years of deposition each, are separated by diastems some of which seemingly represent hundreds of years. The strata are grouped in four divisions which thin alternately to left and right in accordance with changes in off-shore current. The stratum covered by the hat disappears toward the right into a bedding plane. Horizontal exposure, 60 feet. The lower black band is a paved highway.

FIG. 2.—Extreme lensing approximately 4 miles from the nearest ancient strand. Marine lower Pleistocene in Hall Canyon, central Ventura Basin. Notice the cross-bedding, and numerous small and several larger diastems. In basinward parts of a broad epeiric sea it might take several miles to duplicate the lensing shown here in a few feet. The difference would be in large part one of intensity, that is, comparative uniformity and uninterrupted sweep of current. Horizontal exposure, 8 feet.

ing on the correlations of separate field sections which are at equivalent time horizons, and also on the correlation of wells located in different parts of a basin. Remembering the extreme illustration previously given, we see that as much as 30 feet of strata present in basinward areas may be absent at a contact between conglomerate and sand nearer a strand. When ascertaining the causes of variation between two sections in a basin equivalent in time, we may therefore consider not only areal gradation in texture, but also a splitting of parent beds, and a local absence of some strata.

RELATIONS

Although they affect one another in a most intricate and intimate manner, there is no set relation between such features as thickness, texture, stratification, and continuity. Such features are essentially a compromise between rate of subsidence, transgression or regression of a sea, currents, and the amount, kind, and proximity of materials, and these factors in different combinations may give either the same or different results. For example, rapid subsidence and much material received from the land in one part of a basin, and half as much subsidence and half as much material received from the land in another part,

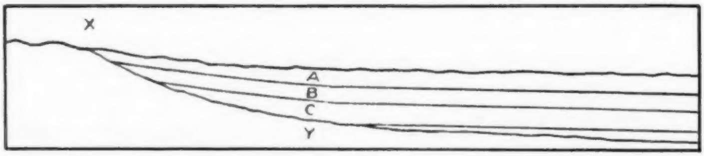


FIG. 3.—Illustrating some distinctions between progressive overlap and unconformity. At *X*, the overlap of *A* upon *Y* is good evidence of unconformity between *A* and *Y*. Unconformity between *A* and the absent formation *B* or *C* does not necessarily follow.

In general (1) overlap proves unconformity only between formations which are present; (2) it does not prove unconformity between a formation which is present and another which is absent at the overlap.

can result in pronounced areal thinning of a succession without the necessity of areal change in average texture, stratification, or continuity of deposits. Or, considering an areally equal subsidence and reception of materials, areally different currents may rearrange the order in by-passing and discontinuous deposition in such a manner that sections equal in thickness differ markedly in other aspects.

Equivalent and apparently complete marine sections of the Pliocene series in Ventura Basin (Santa Paula monocline compared with the area

east of Piru) differ in thickness approximately as 2.2 is to 1, and yet the average texture and stratification of the sections is somewhat similar. Another aspect is furnished by the practically complete Fernando succession on the Santa Paula monocline, which varies markedly in average texture and stratification parallel to the strand, with hardly any perceptible change in thickness.

An unconformity of emergence is not necessarily present or absent because a succession is thinner or thicker at one locality than at another. Unconformity is more closely related to the structure of a basin, and to the kind of movement. A basin of low structural curve would tend to acquire regional unconformity as a result of even minor epeirogenic uplift. A basin of high structural curve would resist and to a certain extent restrict unconformity originating in epeirogenic uplift, because orogenic downwarping at its center might be greater than the regional elevation. This latter phenomenon determined in large part the persistent marine records in California. Net subsidence as a result of orogenic resistence yields, however, to major epeirogeny such as that of the Quaternary, which dwarfed the downwarping in foredeeps such as Ventura Basin[1] and northern India,[2] and held these downfolding deeps above sea-level seemingly for millions of years.

BRACKISH-WATER ASPECTS

Change from marine to brackish-water conditions appears to have a perceptible effect on by-passing and discontinuous deposition. The Fernando sediments in Ventura Basin, for example, show a decrease in distinct bedding at such times as brackish-water conditions encroached from the east. The irregularity of gravel, sand, and clay layers increased, and obvious local scours resulted in prominent but not necessarily long diastems. Between marked scours, the sediments grade laterally in texture with considerable rapidity, strata tend to merge vertically with one another, and distinct bedding planes can be followed only a short distance.

These features are those which might be expected to accompany a condition of universally shallow waters connected with the sea, where the influence of tides alternates with that of erratic currents during storms.

[1] J. E. Eaton, "Divisions and Duration of the Pleistocene in Southern California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 111-41.

[2] Robert V. Anderson, "Tertiary Stratigraphy and Orogeny of the Northern Punjab," *Bull. Geol. Soc. Amer.*, Vol. 38 (1927), pp. 665-720.

J. Marvin Weller, "The Cenozoic History of the Northwest Punjab," *Jour. Geol.*, Vol. 36 (1928), pp. 362-75.

The presence of deltas and of some fresh-water deposits locally is to be suspected at this stage, particularly if large rivers are involved. In Ventura Basin, the first stage of brackish-water conditions seems to have been attended by a universal shallowing of waters through decrease in transportation facilities, and a widespread prevalence of features somewhat but not entirely similar to those associated with strandward marine bottoms.

Computed from California aspects, brackish-water conditions are most commonly inaugurated by (1) decrease in rate of subsidence, and (2) increase in rate of erosion on the land. Locally brackish waters in California have been associated with times of diminished subsidence and with regression of the sea in the later Miocene and the middle Pliocene. They are comparatively rare in transgressing seas of early Miocene and upper Pliocene time. The only truly regional brackish waters of post-Oligocene(?) time in California are those following increased erosion of the land at and succeeding the inception of the Quaternary revolution. As the California seas during parts of this time were in flood (Fig. 11), an increase in amount of material seems to have been involved.

The sedimentary mechanics by which brackish-water conditions are inaugurated appear to be somewhat similar in both factors. These are, seemingly, a raising of the profile of equilibrium with resultant narrowing and shallowing of marine inlets, that is, a concentration of coarse particles, which diminishes the transportation facilities established under previous marine conditions, by restricting the circulation of marine currents. With decrease in rate of subsidence (commonly a short-term factor), the means of transportation become insufficient to maintain a former status, and a basin is overloaded because of its decreased vertical, and therefore decreased cubic, capacity. Marked increase in erosion of the land (commonly a long-term factor) not only overloads previously adjusted transportation facilities, but tends to keep these overloaded with relation to basin capacity by causing a persistently large residue of coarse particles with resultant shallow waters and restriction of marine inlets.

Other factors such as local barriers to marine circulation raised by orogenic uplift near an outlet may be present, but the writer considers such to be ordinarily of minor importance when compared with the causes previously mentioned.

A change from marine to brackish-water conditions seems to record a turning-point in the history of a basin. Alternation of marine and

brackish-water sediment many mark only the turn of rhythmic cycles in sedimentation. Persistent brackish waters may forecast local emergence, or, if world-wide, a revolution. In the latter connection, it seems significant that both the Lafayette formation[1] of the southern United States and the transitional Pleistocene formations of California record fairly widespread depression, both have an absence of the regionally marine conditions which might be expected to accompany such depression, and both herald and precede the greatest degradation of Cenozoic time in their respective districts.

A close approach toward lacustrine conditions, with a further decrease in or absence of marine current, involves other changes. Except near the mouths of streams and in very shallow waters, sediment then grades laterally with considerable regularity in texture, has even bedding and marked persistence, and discontinuous deposition is at a minimum due to the prevailing weakness of currents.

RECAPITULATION OF EQUATIONS

With areally equal subsidence, accumulation takes place at approximately the same average rate and to the same aggregate thickness in all parts of a district undergoing adequate sedimentation, regardless of areal changes in texture, bedding, or other feature of the deposits. With areally unequal subsidence, accumulation takes place at a rate and to a thickness depending on the local subsidence, and is equally independent of compared average texture or bedding.

As the total subsidence below sea-level and the thickness of sediment deposited between two baselevels of deposition are roughly complementary, the thickness of conformable sediment laid down provides a key to the amount of subsidence during its deposition. Parts of a basin, or two separate basins, may therefore be compared and interesting relations be inferred.

When estimating absolute subsidence from a conformable neritic succession, compaction and other distortion occurring subsequent to the close of deposition should be computed and allowed for. Such features may be disregarded when examining equivalent sections merely to secure a relative comparison, for the errors tend to balance one another under similar conditions. Simple working equations can be considered reliable

[1] W J McGee, "The Lafayette Formation," *U. S. Geol. Survey Ann. Rept. 12*, Part I (1891); "Two Erosion Epochs—Another Suggestion," *Science*, n.s., Vol. 3 (1896), pp. 796-99.

Some geologists have included with the Lafayette overlying formations which McGee considered to be highly unconformable with it.

only within the limits of a conformable succession laid down under conditions of adequate sedimentation. Unconformities of emergence are a chief stumbling block. The question of adequate sedimentation need cause little concern within the borders of continents, for sedimentation has probably been adequate in most epeiric seas and on neritic parts of continental shelves.

IV. Illustration By Districts

Foreword.—Barrell[1] has summarized general relations so much better than could be done by the writer, that they are presented by quoting him extensively, as follows:

> ....Because of the present great elevation of the continuents, because of the magnitude of recent orogenic movements, and because of the pulsatory nature of the Pliocene-Pleistocene uplifts, forming an accelerated series, a concurrence of factors has taken place each of which makes for a high rate of denudation. Their combination must give a rate very much greater than the mean for geologic time.....
>
> The Pleistocene history shows that the aggregate motion of uplift has been not merely discontinuous uplift, but that movements of submergence took place between each emergence, and the land at the present time is in a submergent phase, but not necessarily now in movement.....Over the Atlantic coastal plain of the United States the submergent phases of the Pleistocene movements are represented by deposits more or less eroded, the older showing much greater erosion than the younger....McGee, in fact, is inclined to estimate post-Lafayette time as from five to ten million years in length[2]....The uniqueness of the Pliocene-Pleistocene movements lies in the great mean heights which the constituents have attained.....
>
> The ancient epeiric seas were typically very shallow-water bodies.... The widespread marine sands and silts of these seas show the effectiveness of wave action in agitating the bottom material and working it by oscillatory action to great distances.....
>
> The fact that these shallow seas were not speedily filled with sediment and converted into river plains shows that erosion was slow. The greater areas of the land were flat and but little above the sea. Mountain axes alone were the regions of pronounced relief. The retreat of the seas from the continents required a falling sealevel of not more than a hundred, or at most a few hundred, feet. Over broad land areas the elevation was so slight and drainage was so sluggish that when the seas returned they commonly came to rest directly on the uneroded sediments of the previous periods.....
>
> The long crescendo of orogenic movements which ended in the Permian revolution gave rise to great mountain systems, but did not materially elevate the continents, as shown by the preservation of broad mantles of Pennsylvanian

[1] Joseph Barrell, "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. Amer.*, Vol. 28 (1917), pp. 747-75.

[2] W J McGee: Note on the age of the earth. Science, vol. xxi, 1893, p. 309.

and Permian sediments. . . . At the close of the Cretaceous another great revolution was inaugurated—the Laramide—and the average elevation of the lands may have resembled that of the close of the Paleozoic. . . . The Neocene revolution is so close to the Laramide, compared with the length of the older eras, that the latter revolution may be regarded as a preliminary stage leading up to a crescendo, much as the Pennsylvanian movements preceded and led up to the greater Permian movements. . . . .

The Pleistocene represents one of the crescendoes. It has been marked by an acceleration in crustal uplift and oscillation which has raised high the rate of total denudation. Compared to the rate for the whole of the Cenozoic era of revolution, it may be many times the mean. The concurrence of the longer rhythm in sealevel, giving wide and high continents, with the rising diastrophism of a period of revolution may, however, make the present rate of continental denudation ten or fifteen, or even twenty, times the mean for all of earth history, our knowledge of the Precambrian being especially vague. Estimates of geologic time based on measurements of the present rate of denudation and coupled to the assumption that this is the mean for all the past are likely to err accordingly.

VENTURA BASIN

Ventura Basin has been selected to illustrate the major conclusions reached by the writer, because the bulk of the data was worked up there. Accumulation in this basin has been uncommon from the standpoint of thickness and major conformability of the sediment, but the sedimentary mechanics have been practically identical with those operative in other neritic basins, the difference being almost entirely one of intensity. Sedimentation in a part of the territory mapped has been treated by Cartwright,[1] who has carefully reported on certain features which need not be again discussed. The general geology of the basin has been described by several writers.

HISTORICAL GEOLOGY

Heavy and conformable sedimentation took place in parts of Ventura Basin during the middle third of the Cenozoic era, this having been due to a combination of four features. (1) The basin is part of a crustal block which was probably rotated during this time about a horizontal axis in such a manner as to depress southern parts. (2) Its southern edge was locally being let down along a major fault. (3) Northern parts were being folded and shoved southward, forming a complementary trough in this direction. (4) Large quantities of material were received and spread by powerful currents in an elongate bay. Such features

[1]Lon D. Cartwright, Jr., "Sedimentation of the Pico Formation in the Ventura Quadrangle, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 235-69.

were not uncommon in California, where tilting crustal blocks caused a network of inland seas.

Figure 4 shows the position of Ventura Basin in the Pacific geosynclinal belt or zone of contact between the American continental and Pacific segments. This zone has been split into numerous crustal blocks having different sizes, shapes, elevations and tiltings. The blocks are prevailingly arranged *en échelon* in lines which commonly strike northwesterly at a perceptible angle to the strike of the geosynclinal belt. The only combination known to the writer which is capable of causing this particular arrangement is differential horizontal movement involving rotation.

At a time not later than early Eocene, and possibly much earlier, a deep-seated east-west zone of adjustment developed near 34° N. Lat. and extended through southern California and vicinity. This zone was first recognized by Blake,[1] and was named by him the *transverse chain.* It is fairly old, for not only were the local Cenozoic and possibly late Mesozoic basins controlled by it, but differential movement along the San Andreas rift fault has offset it horizontally some 24 miles. It may be related ancestrally in some manner to the northern edge of what Schuchert[2] has called the Sonoric embayment of early Paleozoic time, and may therefore have had an ancient cause.

Greater Ventura Basin embraces the westernmost group of crustal blocks in the transverse chain. The peculiarly discordant position and strike of this basin have caused it to be a take-up line subject to abnormal warping, shortening, and overriding.

Figure 5 outlines Ventura Basin as it exists to-day. The basin can be traced on hydrographic charts for approximately 50 miles farther west than is shown in this figure. The area to be discussed comprises a local trough opposite a resistant mass indenting the southern edge of the basin proper. This mass staunchly opposed lateral movement, whereupon a high-angle fault developed between mass and basin proper, and became exceedingly active in post-Oligocene time. The lateral forces exerted met the obstacle by deepening the local syncline at the point of resistance, with the result that the trough shallows east and west from the indenting mass. The trough is plainly a small foredeep resulting from compression against a resisting buffer.

[1]W. P. Blake, "Pacific Railroad Reports, Explorations and Surveys," *U. S. War Dept.*, Vol. 5, Pt. 2 (1856), pp. 51, 55, 133.

[2]Louis V. Pirsson and Charles Schuchert, *Text-Book of Geology*, John Wiley & Sons, (New York, 1924), Pt. II, p. 139.

FIG. 4.—Transverse chain with reference to the southwestern United States. Contours of elevation at 2,000 and 5,000 feet, with elevations more than 8,000 feet shown in black, are after the U. S. Geol. Survey relief map. The structure of Ventura Basin strikes east and west, in marked contrast to the prevailing northwesterly strike of the Pacific geosynclinal belt.

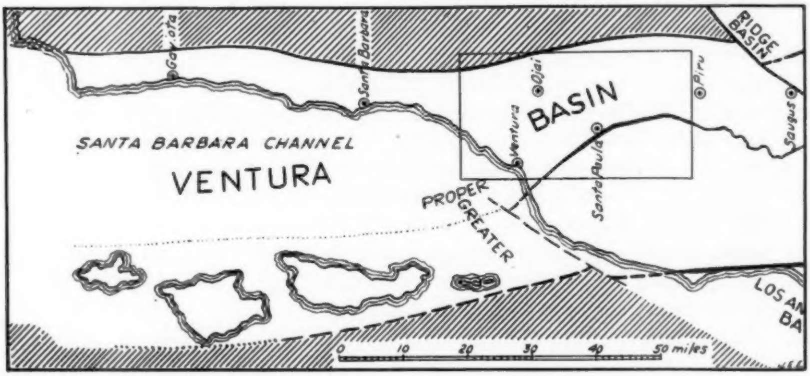


FIG. 5.—Middle and eastern Ventura Basin, showing relation to some adjoining basins and other areas. The rectangle outlines Figures 6, 7, 8, and 9.

Figure 6 illustrates the lower and middle Pliocene sea in a part of the Ventura Basin embayment. In California as a whole, this was a time of rather coarse-textured sedimentation, with regression and small extent of the sea.

Figure 7 illustrates the upper Pliocene sea in the same part of the Ventura embayment. In California as a whole this was a time of more fine-textured sedimentation, with transgression and wider extent of the sea.

Figure 8 presents features of the transitional Pleistocene sea in the same part of the Ventura embayment, a time of predominantly coarse-textured sedimentation and very small extent of *marine* conditions in California as a whole. The Quaternary epeirogenic movement has started, and the strand lines are oscillating preparatory to one of the major regressions of the sea in geologic time. (The lower Pleistocene series proper, which is not illustrated in contour, was somewhat similar to the transitional phase except that conditions were more variable and marine sediments were of even more restricted extent.)

Cross sections in the upper left corner of Figures 6, 7, and 8 show approximately how the local trough was progressively downwarped as a complement to upfolding on the north. The trough parallels the ancient Santa Ynez anticline, a large fold on the north which later moved southward and appears in Figures 8 and 9. The growth of this large anticline eventually caused the parallel Sulphur Mountain anticline to form farther south, to become emergent in the later Miocene, and to grow steadily throughout Pliocene and lower Pleistocene time. The northern strand of Ventura Basin consequently receded southward, and the trough narrowed. (But notice that the southern strand was in later times transgressing southward upon the resistant buffer.) Finally, during the Quaternary revolution, the Sulphur Mountain anticline was overturned southward upon the trough. It now forms a recumbent fold, the western end of which passes underneath the Red Mountain thrust, and the eastern end under the San Cayetano thrust (see sections, Figure 10).

The sedimentation indicated in Figures 6, 7, and 8 was almost entirely marine. It was seemingly conformable in the deepest parts of Ventura Basin. Unconformities, including two within the later Miocene and a large one between the lower and the upper Pliocene, are present on outer edges of the trough.[1] The contours showing lines of equal

[1]The middle and uppermost Miocene and the lower and middle Pliocene series are absent south of the Santa Clara River fault, that is, south of Ventura Basin proper.

The embayment extended at times at least 25 miles farther east or inland than is shown in Figures 6, 7, and 8, in general widening. Brackish-water and unconformable features appear at certain horizons east of the strait. These features encroached west of the strait toward the end of lower Pleistocene time as the sea shallowed and prepared to withdraw.

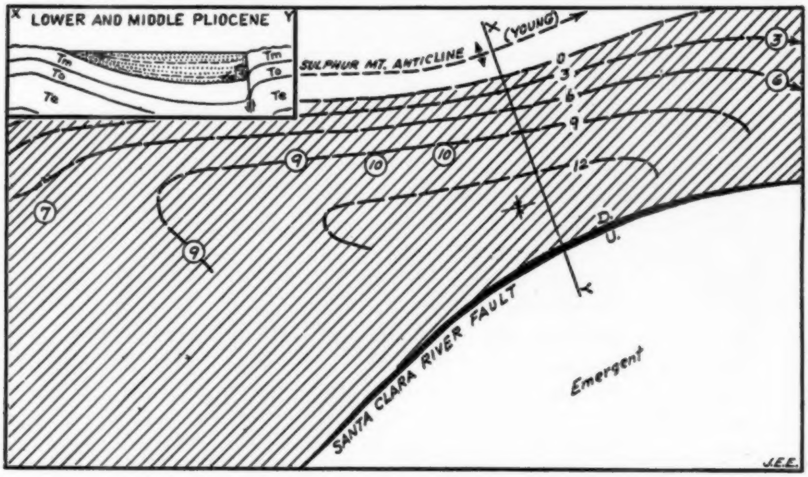


FIG. 6.—*Lower and Middle Pliocene.* Comparative total subsidence below sea-level and thickness of sediment deposited. Shading shows average area covered by the Santa Paula sea. Contours approximate 2,700-foot intervals, with a unit representing approximately 900 feet. Regressing seas in California as a whole.

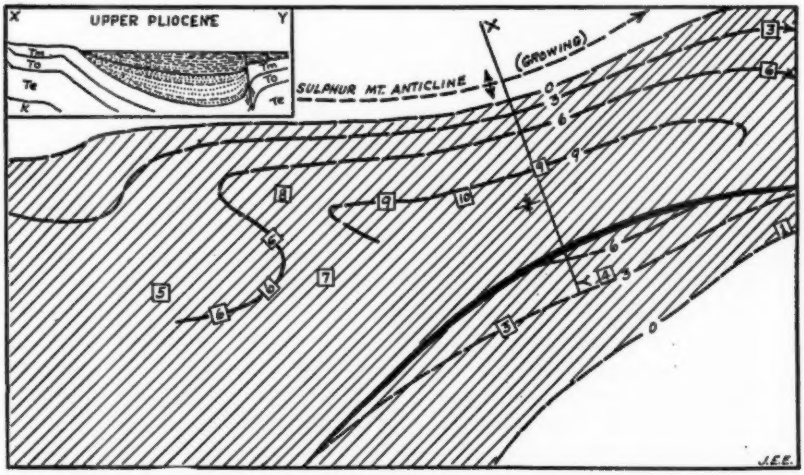


FIG. 7.—*Upper Pliocene.* Comparative total subsidence below sea-level and thickness of sediment deposited. Shading shows average area covered by the Pico sea. Contours approximate 1,800-foot intervals, with a unit representing approximately 600 feet. Transgressing seas in California as a whole.

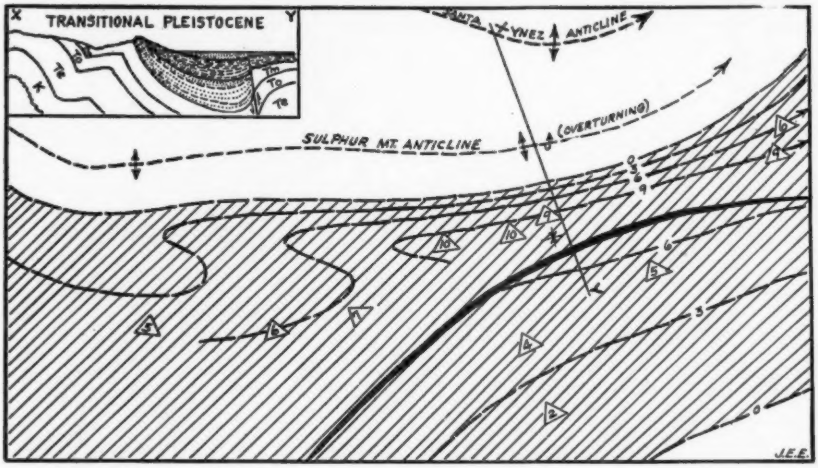


FIG. 8.—*Transitional Pleistocene.* Comparative total subsidence below sea-level and thickness of sediment deposited. Shading shows average area covered by the Saugus sea. Contours approximate 525-foot intervals, with a unit representing approximately 175 feet. Transgressing seas still predominate in California as a whole, but growing diastrophism and coarsening of sediments forecast regression and brackish waters in lower Pleistocene time.

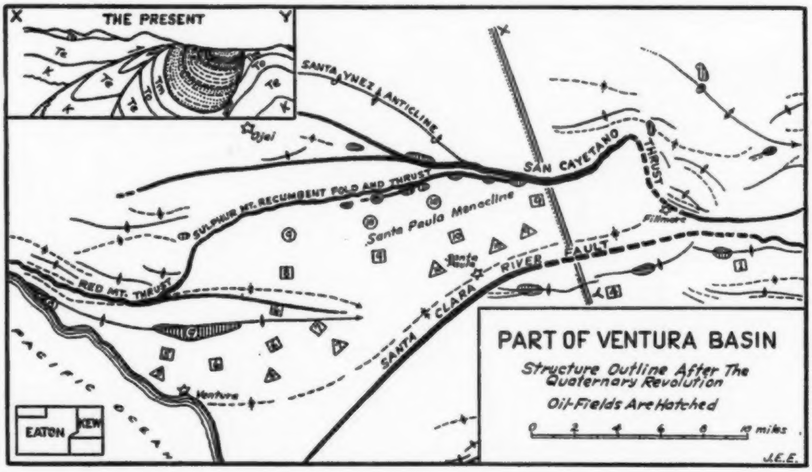
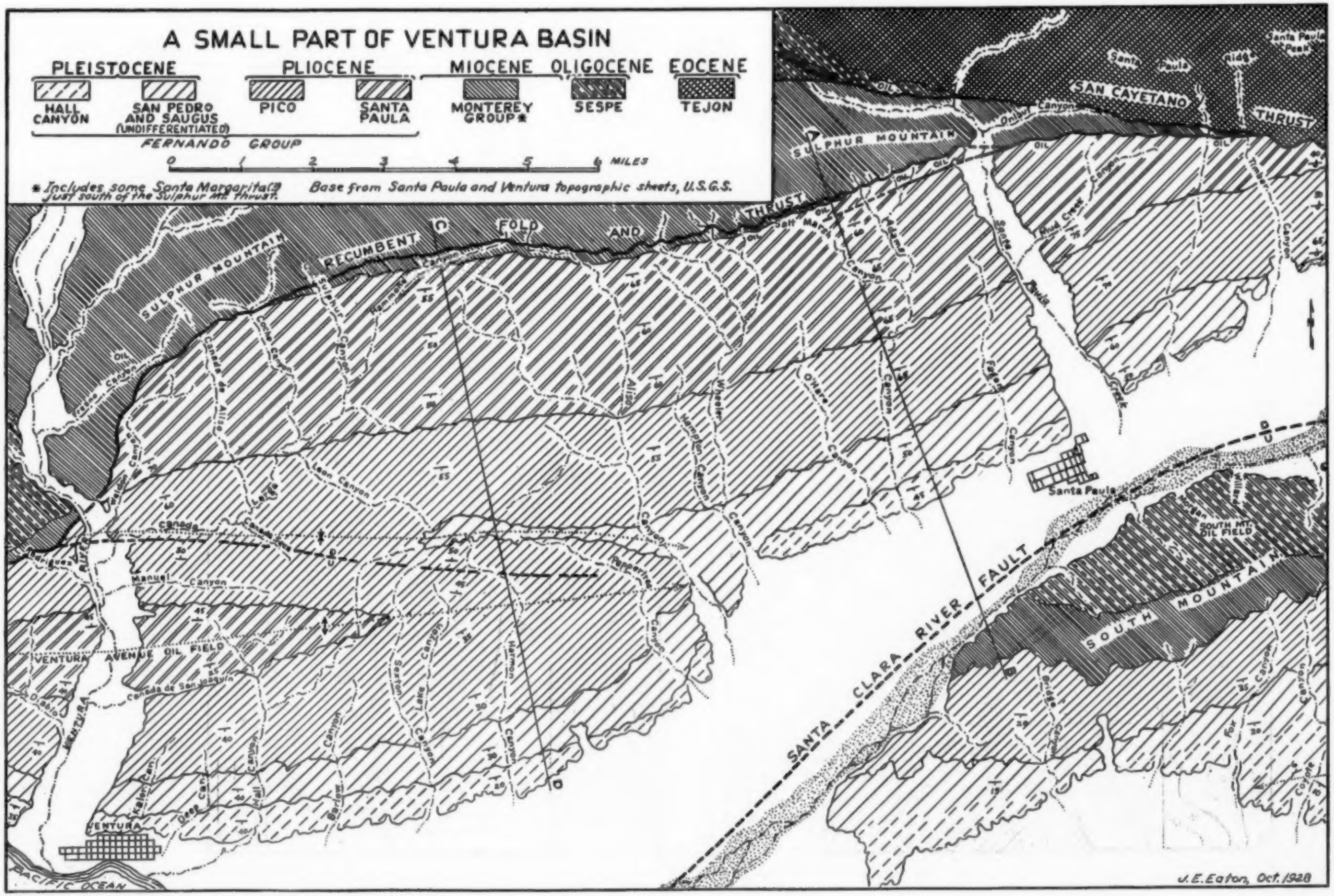
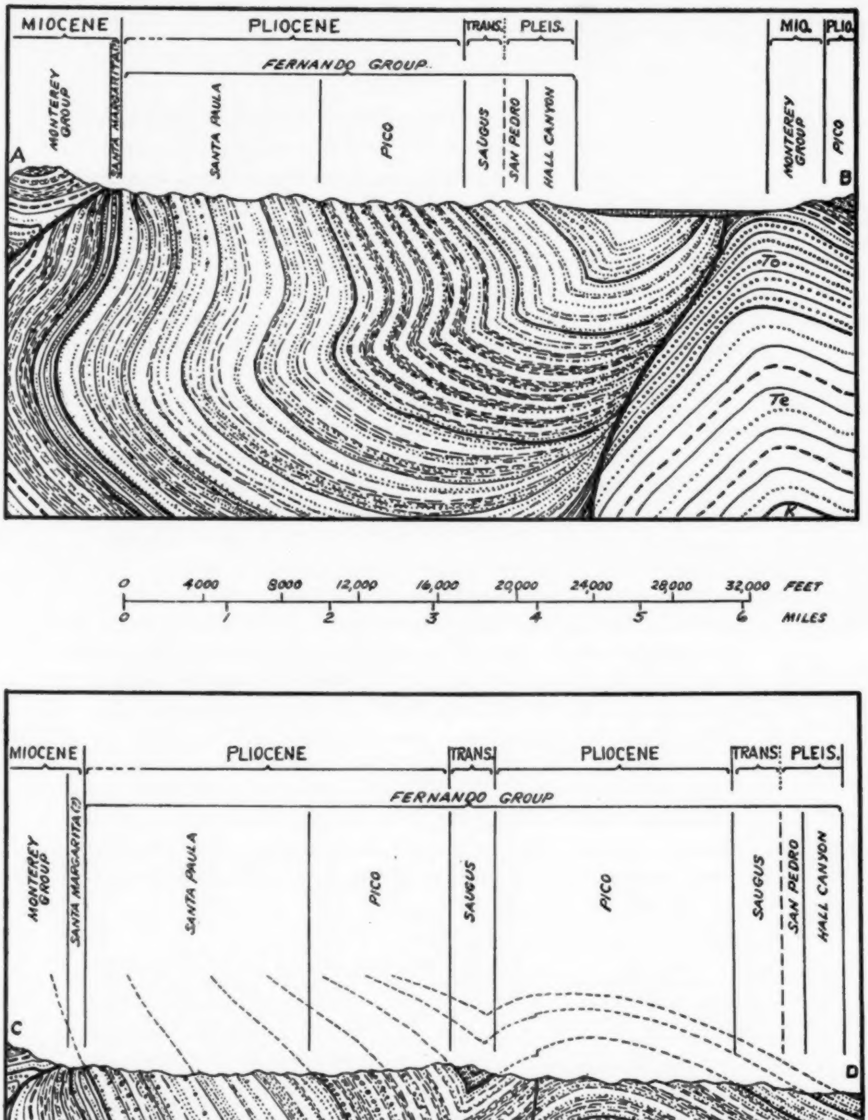


FIG. 9.—*The Present.* The same area shown in the preceding three figures. The basin has been shoved southward and shortened in this direction from 30 to 50 per cent, with older rocks locally thrust over younger.



A SMALL PART OF VENTURA BASIN
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
HALL CANYON
SAN PEDRO AND SAUGUS (UNDIFFERENTIATED)
PICO
SANTA PAULA
MONTEREY GROUP*
SESPE
TEJON
FERNANDO GROUP
0 1 2 3 4 5 6 MILES
* Includes some Santa Margarita(?) just south of the Sulphur Mt. thrust.
Base from Santa Paula and Ventura topographic sheets, U.S.G.S.
SAN CAYETANO THRUST
SULPHUR MOUNTAIN
RECUMBENT FOLD AND THRUST
SANTA CLARA RIVER FAULT
SOUTH MOUNTAIN
SOUTH MT. OIL FIELD
VENTURA AVENUE OIL FIELD
Santa Paula
VENTURA
PACIFIC OCEAN
J. E. Eaton, Oct. 1928

FIG. 10


MIOCENE
PLIOCENE
TRANS.
PLEIS.
MIO.
PLIO.
FERNANDO GROUP
MONTEREY GROUP
SANTA MARGARITA
SANTA PAULA
PICO
SAUGUS
SAN PEDRO
HALL CANYON
MONTEREY GROUP
PICO
A
B
To
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K
0
4000
8000
12,000
16,000
20,000
24,000
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MILES
MIOCENE
PLIOCENE
TRANS.
PLIOCENE
TRANS.
PLEIS.
FERNANDO GROUP
MONTEREY GROUP
SANTA MARGARITA (?)
SANTA PAULA
PICO
SAUGUS
PICO
SAUGUS
SAN PEDRO
HALL CANYON
C
D

FIG. 10

subsidence below sea-level and thickness of sediment deposited are based for the greater part on field sections. These have locally been supplemented by the thickness of foraminiferal zones[1] penetrated in wells, which latter may be considered more uncertain because of possible hidden faulting and a combination of high dip with probably crooked holes.

South of the Santa Clara River fault, regression in the lower and middle Pliocene was followed by a rather progressive transgression of the sea during upper Pliocene and transitional Pleistocene time. Successions of these latter ages are therefore locally fragmental, due to progressive overlap.[2]

North of the Santa Clara River fault, a rather persistent net regression of the sea seems to have taken place somewhat against epeirogenic influence, as a result of the complementary upfolding on the north and downfolding on the south. The strand apparently assumed slowly changing positions as it retreated southward. The positions approximated the comparatively stationary center of a seesaw, the land rising northward and the sea bottom subsiding southward with increasing rapidity. This feature presumably caused thin coarse-textured members near the strand to be equivalent in time to thicker sediment of finer texture basinward.[3]

That the decrease in thickness and dying-out of sediment north from the axis of the trough was primarily due to differential warping, and not to major faulting along the northern strand, is evidenced in several ways. It is sufficient to state that there is not, even now, any fault in the vicinity of the ancient northern strand having a length and vertical throw equal to the uncommon thickness of sediments extending east and west for approximately 50 miles. (The present thrust faults cut the basin at a slight angle, die out rapidly, and the heavy sedimentation crosses their zone upon the east.)[4] Minor northern faulting may, however, have aided the phenomena.

[1] Paul P. Goudkoff, personal communication.

[2] W. S. W. Kew, "Geology and Oil Resources of a Part of Los Angeles and Ventura Counties, California," *U. S. Geol. Survey Bull.* 753 (1924), postulated an unconformity between the Pico and Saugus formations south of the Santa Clara River fault, partly because the Pico formation is overlapped. The present writer has so far not found an unconformity of emergence at the contact, and foraminiferal determinations indicate a gradation. The local thinning and absence of the Pico formation is therefore tentatively ascribed to progressive overlap (see Figure 3 of the present paper).

[3] This phenomenon is also illustrated in the structurally similar Ridge Basin northeast of the area described. The ancient strand, there preserved by faulting and now exposed, shows coarse massive boulder beds grading basinward to equivalent but thicker finer-grained and thinner-bedded phases of sand and shale.

[4] The writer at first suspected that tremendous vertical faulting had taken place along the Red Mountain-San Cayetano thrust zone and had since been hidden by overthrusting. The completed field work shows that the trough and its sediments are not in accord with such a hypothesis, and that it is untenable as regards any major throw.

Figure 9 presents a sketch map of the same part of Ventura Basin as it exists at present, after deformation in the Quaternary revolution. The eastern part of the map is after Kew.[1] The basin was compressed and shortened from north to south 30 to 50 per cent by Quaternary movement. Older rocks were locally thrust over younger ones for a distance of several miles. The maximum exposed thickness of each individual series of the Cenozoic era in the territory mapped is, approximately: Eocene, 9,000 feet (chiefly marine); Oligocene(?), 4,000 (non-marine); Miocene, 7,200 (chiefly marine); Pliocene, 15,450 (marine); transitional Pleistocene, 1,750 (marine); and lower Pleistocene, 2,600 (marine, grading to brackish-water at top). These individual maxima are found at slightly different localities because of a southward shifting of the axis of maximum subsidence during the epochs. When added, they give a Cenozoic succession nearly 40,000 feet thick in the local trough or foredeep, but only approximately 31,000 feet of sediments can be measured along any one section.

Figure 10 shows enlarged areal geology of a central portion of the territory illustrated in preceding figures. The sedimentation discussed took place between the Sulphur Mountain anticline and the Santa Clara River fault. It resulted in forming the Fernando group sediments, a marine succession locally 19,832+ feet in thickness, chiefly of Pliocene and lower Pleistocene age. Compression in this district during much of the Cenozoic era may have been succeeded by tension for a short time during the late Pleistocene, for monoclinal dips near the two jaws of the "nutcracker" are in some areas less than those between, suggesting a late collapse of pressures. In this connection, however, it is to be noted that most of the lateral pressure was exerted somewhat below the level of Sulphur Mountain, which is a very steep and isolated ridge.

REGIONAL ASPECTS

Figure 11 is a highly generalized and in part tentative graph of some regional relations in California during the middle third of the Cenozoic era. Sections have been sketched across deep parts of three basins in such a way as to show maximum conformability. It is possible that the maximum unconformity shown in the later Miocene and also in the middle Pliocene was total for a time, but if such totality existed it was of rather short duration. Folding and erosion subsequent to deposition are not considered in the drawing. Unequal thicknesses have been reduced to an average, that is, time equivalency. Practically all sediments

[1] W. S. W. Kew, *op. cit.*

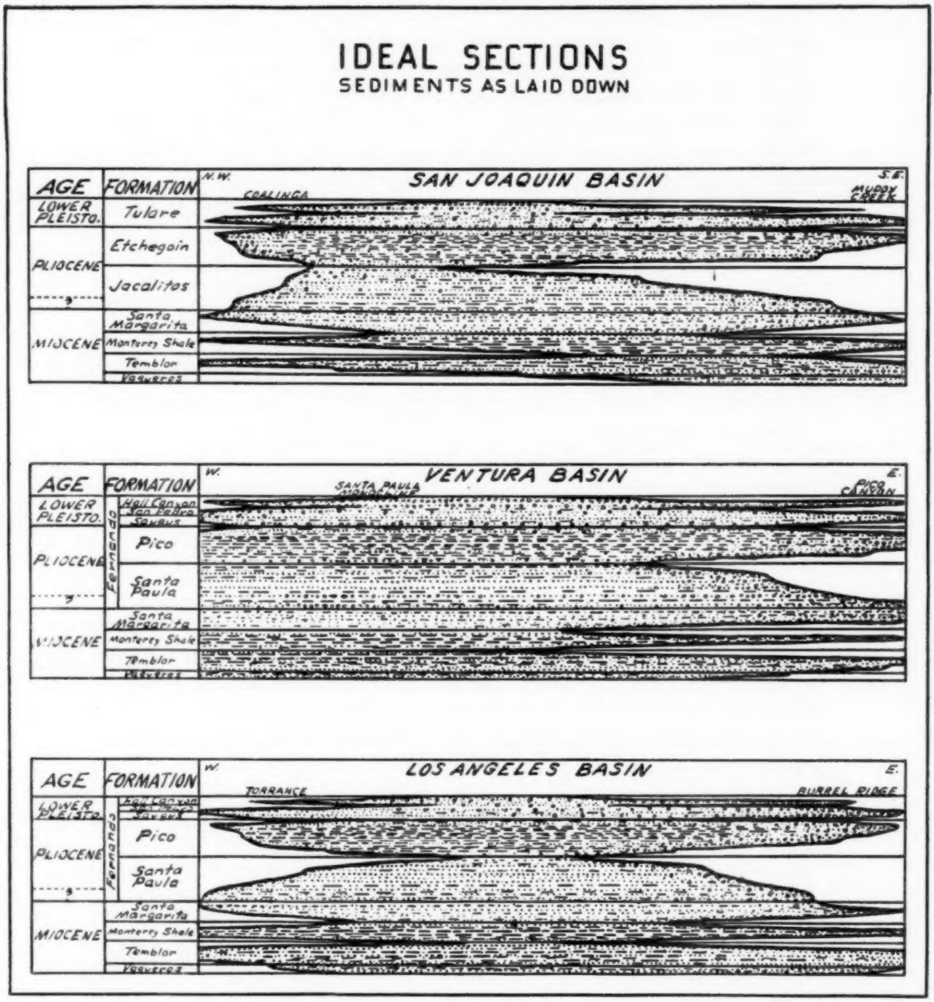

FIG. 11.—Generalized and in part tentative sketch of epeirogenic transgression and regression of seas in California during the middle Cenozoic (local orogenic variations ignored). The lower Pleistocene waters were in large part brackish. The marine record is lost at the close of the lower Pleistocene for a period of several million years.

shown are marine, except for the lower Pleistocene, which is marine only in western parts of Ventura and Los Angeles basins. Sedimentation was at nearly all times persistently adequate, and the deepest waters in those parts of the basins now exposed probably in few places exceeded a few hundred feet. Adequacy of sedimentation commonly increased in efficiency during times of marine regression, a feature interpreted as indicating that (prior to Pleistocene time) a rate of subsidence influenced features of sedimentation more than did a rate of erosion on the land, or at least was influential. The restricted waters passed more of the finer particles received on to outer edges of the continental shelf.

The first Miocene (Vaqueros and Temblor) transgression in California was somewhat persistent, with an increasing organic content in the sediments. Regression about the middle of Miocene time was followed by a transgression during which almost pure diatomite (the Monterey Shale) was locally included in sediments laid down. Another regression in the upper Miocene was followed by transgression and predominantly clastic deposition (Santa Margarita).

Pronounced regression accompanied by clastic deposition took place in the lower and middle Pliocene. Transgression and finer-grained clastic deposition then followed in upper Pliocene time. (Texture refers to the degree in which the finer particles were retained near the land.)

The inception of the Quaternary revolution did not immediately remove the waters from California, but it rapidly cut the inland seas off from good marine circulation. Extensive coarse-textured and nonmarine sedimentation inland shows that a deluge of material, assisted by a breaking down of transportation facilities, shallowed the waters and reduced the marine inlets. A major upward trend started at an early date, however, the seas then completely withdrew, and the marine record is lost until very late in the Pleistocene. Ventura Basin participated, with orogenic modification, in these epeirogenic movements of post-Oligocene time.

STRATIGRAPHY

Table I outlines the middle and upper Cenozoic chronology in Ventura Basin, and also the prevailing texture of the exposed sediments. The Miocene-Pliocene contact is drawn approximately 1,750 feet stratigraphically lower in the present paper than in an earlier one by the writer,[1] larger and better faunas having indicated a preponderance of supposed

[1] J. E. Eaton, "Divisions and Duration of the Pleistocene in Southern California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), Fig. 1, p. 115.

Pliocene forms in disputed sediment previously referred to the uppermost Miocene.

The warm, lagoonal seas of Miocene time in California were to a large extent intercommunicating, there was a regional extent of diagnostic fossils, and the custom of referring formations of this age to the standard column[1] of California has been followed in Table I. The restricted Pliocene and lower Pleistocene seas, on the other hand, were practically all separated as regards basins, diagnostic forms were less regional in habitat, and the custom of using provincial names for formations of these ages has been followed in the table.[2]

The lower 15,450 feet of the Fernando group sediments exposed in deep parts of Ventura Basin (see Fig. 10, section *A-B*) were laid down with seeming conformity during the Pliocene. At 15,450 feet above the base of the succession, the inception of the Quaternary epeirogenic movement furnished more materials, and caused the rate of subsidence to become more variable. At 18,000 feet above the base, there occurred a pronounced hesitation in subsidence which was accompanied by local unconformity. At 19,832 + feet above the base, the increasing strength of the great Quaternary forces terminated sedimentation, and the basin participated, rather tardily, in what was perhaps the most widespread upward movement since the Permian. The marine record is lost at the close of the lower Pleistocene and is not regained for several million years. During the interim the region was severely deformed, with the result that the San Cayetano-Red Mountain line developed overthrusts. The older rocks on the north rode southward along these thrusts, the strata were tilted to almost their present inclination, and enormous degradation took place.

MATERIALS AND CAPACITY

Much of the material forming the sediments dealt with was derived from the discharge of comparatively short streams flowing from the north. This is known from the direction and manner of gradation in texture of the sediments, and from the feature that most of the larger particles are fragments of Cretaceous(?), Eocene, Oligocene, and Mio-

[1]The typical *Santa Margarita* is the upper Miocene type which probably encroaches least upon the *Monterey Shale*. The latter term takes precedence over all conflicting nomenclature in a standard column for California.

[2]For those who would approach a more complete standard marine column for California: the Santa Paula approximates the *Purisima;* the Pico (restricted) occupies the stratigraphic position of the *lower Merced;* the Saugus includes the *upper Merced*. The *San Pedro* and *Hall Canyon* are indicated to be unique marine horizons, therefore to be of themselves standard.

TABLE I

MIDDLE AND UPPER CENOZOIC CHRONOLOGY IN A PART OF VENTURA BASIN

Age			*Formation*	*Maximum Thickness in Feet*	*Remarks*
Pleistocene	Champlain		Terraces emerging		Elevation
	Glacial		(Erosion of 5,000 ± feet of rocks)		Depression
	Sierran				Elevation (net)
	Pedroian	Fernando group	Hall Canyon	1,800	Sand, clayey sand, and gravel
			San Pedro	800+	Sand, clayey sand, and gravel
	Transition		Saugus	1,750−	Sand, clayey sand, and gravel
Pliocene	Upper		Pico	6,200	Bluish-gray clayey sand and grayish-blue clay with interbedded sandstone and local gravel. Commonly sandy at extreme top and conglomeratic at base
	Middle and Lower		Santa Paula	9,250	Heavy-bedded gray to blue arkosic sandstone, with lesser members of thin- and medium-bedded sandstone and brown and blue clay. Locally conglomeratic (7,500) Calcareous sandstone and brown and blue sandy clay. Locally conglomeratic (1,750)
Miocene	Upper		Santa Margarita	1,500	Shaly sand, white granitic sandstone, and gravel
		Monterey group	Monterey Shale	5,700	Diatomite, siliceous shale, limestone, and white, gray, and tan sandstone. A base of sandstone with dark to black clay shale
	Lower		Temblor		
			Vaqueros		

cene strata which were being elevated in this northern area. The more important streams from the northern flank evidently had their outlets approximately 10 or 12 miles apart, with smaller intervening streams. The points of discharge shifted slowly during the ages and varied these intervals somewhat. An undetermined proportion of the material, chiefly the finer, was derived from the east. Eastern parts of the embayment received the discharge of streams, kept most of the coarser particles, and passed many of the finer particles on westward to the territory illustrated. The matrix of certain lower and middle Pliocene sandstones is, moreover, rather freshly arkosic, and the most available sources of fresh feldspar were granitic rocks exposed on the east and northeast. A small part of the materials was doubtless furnished by wave action along the strand, and another minor part from emergent parts of the buffer southeast of Ventura Basin proper.

Subsidence was practically continuous in central parts of the trough during the deposition of the greater part of the succession, but the rate of this seems to have been increased or retarded at times. The prevailing texture of the sediments and the average depth of water varied in cycles of somewhat irregular duration. The longer cycles seem to have been determined by long-continued diastrophic and possibly climatic swings, the shorter ones (rapid alternation of coarse- and fine-textured beds) by variations in current during lesser periods of time. Different parts of the district subsided at different rates (Figs. 6, 7, and 8), for, while a temporary baselevel of deposition was attained or approached at short intervals in all parts of the area, the thicknesses of sediment in full and conformable sections are different. A slow submarine growth of the Ventura Avenue anticline seems to have started about the middle of Pliocene time, and this may have aided the subsequent comparative thinness of accumulation which is evidenced on parts of this structure.

Most depths of water were almost certainly less than 600 feet, for even the upper Pliocene clays contain lenses of gravel. The profile of equilibrium is near or above this depth on much of the present continental shelf under conditions of pronounced recent scouring.[1] What the average depths of water were the writer has no idea, except that for long periods of time they were very shallow. Owing to persistently adequate sedimentation, maximum depths of water did not always follow lines of maximum subsidence, but rather followed the path of off-shore currents.

[1]The coast has lately been elevated, locally as much as 1,200 feet. As the continental shelf is now, except for drowned valleys, very flat out to or near the 100-fathom line, at least the later part of this elevation must have been accompanied by submarine erosion in the neritic zone and a shifting of scoured material to deeper waters.

This is shown by local relations of texture to thickness. In post-Miocene time the maximum depths of water were considerably south of the axis of maximum subsidence on the west, but converged into or near this axis eastward at the strait.

EXPOSED SECTION

Aspects of the upper Pliocene and lower Pleistocene series can be examined or computed in some detail within a triangular area approximately 15 by 4 miles on a right angle. Relations may be approximated from discontinuous exposures throughout an area many times as large. Owing to the rapid gradation characteristic of California basins in particular and of Cenozoic time in general, the distances mentioned may be compared with distances of perhaps 200 and of 50 miles respectively in some broad and ancient epeiric seas.

ESSENTIAL RELATIONS

The part of the Ventura embayment shown in Figures 6, 7, and 8 was seemingly an area of disseminated accumulation,[1] adequate sedimentation, and adequate currents, in post-Oligocene time at least. The succession then laid down illustrates most of the data mentioned in the present paper, and is the typical locality of many of these.

The essential relations to be grasped are: that subsidence was areally very different in amount; that, despite this feature, shallow waters and an almost flat,[2] even, and balanced sea bottom were maintained at all times; and that thickness of sediment parallels subsidence and not texture or bedding. These relations imply a neritic environment with active by-passing and discontinuous deposition, and the visible evidences of such in the field are legion.

When the circumstance is once thoroughly grasped that neritic bottoms are practically balanced at nearly all times, and have, in a sense,

[1]Cartwright (*op. cit.*, p. 253) considered certain marine conglomerates in the area to represent deltaic accumulation, basing his conclusion on the great thickness of coarse-textured zones, poor assortment of material, angularity of some pebbles, lenticularity of layers, and current bedding. The present writer considers no feature presented by these marine sediments to be peculiar to deltas, and all to be consistent with disseminated accumulation under the conditions. The phenomena are those to be expected off-shore from the mouths of turbulent streams discharging material into powerful marine currents—a retaining of very coarse particles near the bar, with marked by-passing, scouring, discontinuous deposition, and intermittent rapid burial after long diastems.

[2]The necessarily exaggerated vertical scale of many drawings causes some students to visualize neritic sedimentation as a process of particles rolling down a steep slope by means of gravity. Such a view is almost totally erroneous, for the average neritic bottom has an average slope of less than 1°, and a slight change in current may cause particles to move upslope almost as easily as down.

the power of either accepting or rejecting sedimentary material, the origin of various secondary features previously discussed becomes clear. Such secondary features need not be illustrated in detail, for the reader can view them for himself in the nearest basin exposing stratified sediment.

COLORADIC GEOSYNCLINE

Figure 12 presents contours showing the comparative total subsidence below sea-level and thickness of sediment deposited, in the Coloradic geosyncline during Upper Cretaceous time. The measurements of seemingly conformable successions used as a key, and decimally expressed in circles, have been taken from selected professional papers and bulletins of the United States Geological Survey.[1] It would be preferable to show the geosyncline in three or four separate figures representative of several stages, for the extent of the sea, the contours, and the axes changed with time as in Ventura Basin. However, as the discrepancy in the compared ideas of the investigators consulted is more pronounced with the smaller units, a comparative total has been selected for presentation.

The sediments of the Coloradic geosyncline are notably shallow-water deposits. According to Lee:[2]

> The rate of sedimentation in this basin was comparable with the rate of subsidence. The sediments and the fossils they contain are of such a nature as to render it improbable that the sea was at any time very deep. It was probably for the most part so shallow that the sediments were somewhat uniformly distributed over its floor by waves and currents.

A combination in the Coloradic basin of persistent and universal shallow-water conditions and adequate currents with the feature that formations aggregating some 14,000 feet in thickness at the center of the western foredeep thin outward, without apparent or at least material unconformity, to a fraction of this thickness, is evidence that sedimentation was at nearly all times persistently adequate, and was closely controlled by the profile of equilibrium through the agencies by-passing and discontinuous deposition.

The average marine bed of the Coloradic geosyncline is strongly contrasted with the average bed in Ventura Basin and in other parts of California by reason of its continuity over comparatively wide areas,—the persistent identity of the major Frontier and certain other sands in

[1] As the publications examined exceed a score, it is impractical to cite these separately in the present brief outline. They may be readily identified and referred to by consulting the "List of Publications," *U. S. Geol. Survey* (1907-24).

[2] Willis T. Lee, "Relation of the Cretaceous Formations to the Rocky Mountains in Colorado and New Mexico," *U. S. Geol. Survey Prof. Paper 95-C* (1915), p. 57.

Wyoming being well known. The contrast with the rapid lensing and gradation characteristic of Cenozoic beds in California is extreme, due to different environments. Conditions in California were those of comparatively high structural curve, short hauls, and eddying or interrupted currents, whereas the Coloradic geosyncline had a comparatively low structural curve, long hauls, and broad sweep of less variable and less interrupted current.

The two basins parallel each other rather closely as regards form and asymmetrical warping during deposition, and also in mechanics of diastrophism subsequent to emergence. In Ventura Basin, the location of the present San Cayetano and Red Mountain overthrusts was early determined by resistant areas south of the present overriding strata, as is apparent from the contours shown in Figures 6, 7, and 8 compared with the structure shown in Figure 9. Similarly, deep parts of the Coloradic geosyncline not only determined the position of much of the present Rocky Mountains and accompanying overthrusts, but the present abnormally high and broad highlands of Colorado were forecast by contours shown in Figure 12 which indicate that the southern bulbous part of the geosyncline was subject to being pinched between buffers whose indenting points were located approximately in northwestern Utah and the Panhandle of Texas. (Notice from Figure 4 that the late Mesozoic positive area on the site of the present Great Basin is now flanked on the west by the high ridge of the Sierra Nevadas and on the east by the present highlands of western Colorado.)

In general, though not in detail, the Ventura and Coloradic basins were similar. Differences in sedimentation were chiefly a result of different intensities, the thickness of seemingly conformable sediment being approximately the same. Ventura Basin was approximately $^1/_{30}$ as long and broad, but was structurally 30 times as steep, as the Coloradic geosyncline. The grading and lensing of its sediments was correspondingly many times as intense. Features of by-passing and of discontinuous deposition are equally applicable to both localities, and in both controlled sedimentation with an iron hand.

CONCLUDING STATEMENT

The writer has endeavored to present a picture[1] of a net almost infinitely complex and flexible, which covers the waters of the earth. This net ceaselessly contracts and expands its mesh in a manner deter-

[1]Consult Beverly L. Clarke, "On the Difficulty of Conveying Ideas," *Sci. Monthly*, Vol. 27 (December, 1928), pp. 545-51.

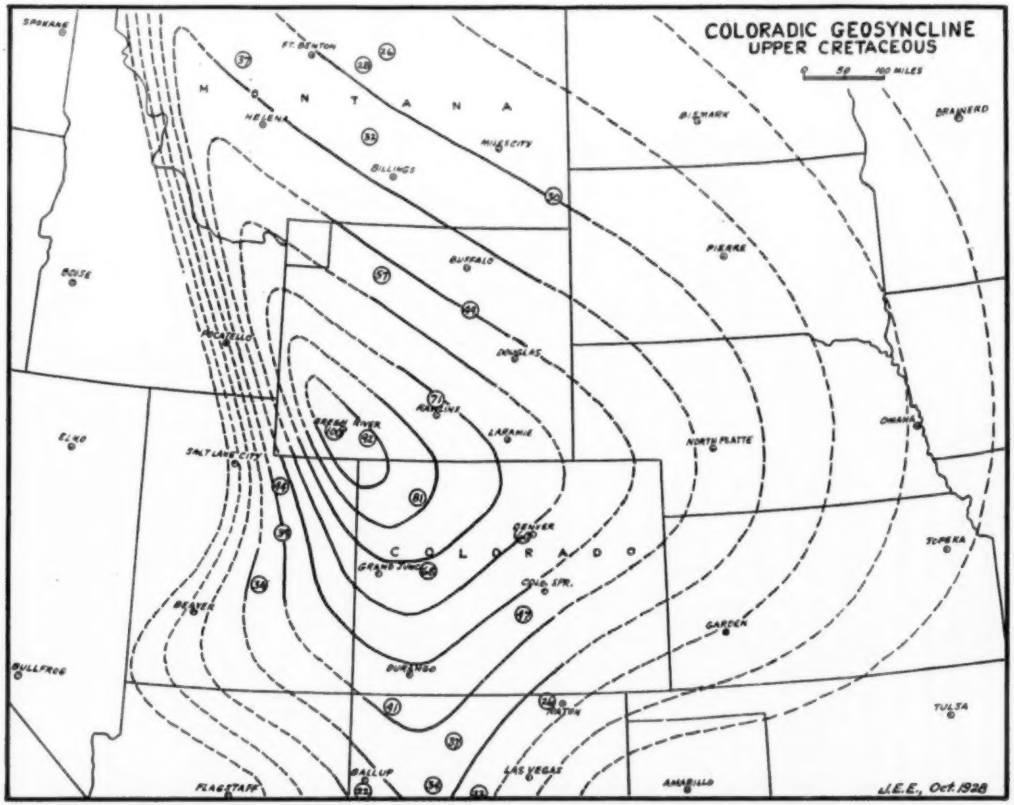

FIG. 12.—*Coloradic geosyncline.* Upper Cretaceous. Comparative total subsidence below sea-level and thickness of sediment deposited. Contours approximate 1,400-foot intervals, with a unit representing approximately 140 feet. The sea gradually receded and became locally brackish. Notice the nutcracker effect between the Great Basin district and the Texas Panhandle, which probably had an influence in determining the synclinal center and the subsequent Colorado highlands. The steep synclinal flank in western Montana is now overridden by a thrust. The thicknesses of sediment, shown decimally in circles, have been calculated from publications of the U. S. Geol. Survey.

mined by existing combinations, thus passing onward different amounts and kinds of sedimentary material. Its more active domain is within the limits of the neritic environment, but within these limits it is supreme, and no particle of material being normally transported by water can come to rest except in accordance with its rules.

Some features which control this net, and other features which it in turn controls, have been briefly discussed. The amount of ground covered in so short a space has resulted in a didactic style of presentation which the writer would prefer to have avoided, particularly as a minimum of supporting evidence and qualification can accompany a brief sketch. It seems likely that some of the conclusions arrived at herein will be modified by other workers, and that as a result of future work the writer will modify some of them himself.

The barest outline of factors has been given. It is believed that some of these deserve the work of many lifetimes, and the recording of this in many volumes. Only by such work can they be moved from the realm of speculation to that of scientific attainment.

TABLES OF TERRANE EFFECTS[1]

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ABSTRACT

These tables of terrane effects have been devised for use in routine commercial surveys with the torsion balance in areas of moderate relief, and for that purpose, they are a slight refinement and improvement over the graphical methods of the calculation of the terrane effects, described by the writer, Haalck, and Heiland. The terrane is divided into (*a*) octants and zones of $5\sqrt[3]{10^n}$ radius, and into (*b*) 22½° sectors and zones of $5\sqrt[6]{10^n}$ radius. Each zone is divided vertically into prisms, and this series of prisms is projected by the law of similar bodies in projection of one another into the other zones of the same octant or sector. The gradient and differential curvature produced by each of the prisms is calculated by the formula for a vertical concentric curvilinear prism in cylindrical coördinates. The effects are tabulated for elevations of 0 to 2 in the 5 to 11 zone (5 to 7.3), and the corresponding elevations in the 11 to 23, and 23 to 50 zones (7.3 to 10.8, 10.8 to 15.9, 15.9 to 23.2, 23.2 to 34.1, and 34.1 to 50 zones). A similar table is given by octants for the zone 0 to 2.3. A somewhat similar table is given for the effects produced by an infinite straight ditch or embankment. These tables, or preferably tables valid to infinite depth, can be used to calculate the effects of anomalous masses in the subsurface.

These tables[3] have been devised for use in routine commercial torsion balance surveys and are a slight refinement and improvement of the graphical method of calculation of the terrane effects. Such graphical methods differing only very slightly have been devised and published independently by Haalck,[4] Heiland,[5] and the writer.[6]

[1]Read before the Association at the Fort Worth meeting, March 22, 1929. Manuscript received by the editor, March 15, 1929.

[2]Consulting geologist and geophysicist, Petroleum Building.

[3]The U_{xy} of these tables is for use with the method in which the coefficient for U_{xy} in the station calculations is used doubled in order to avoid the later multiplication by two in the calculation of the differential curvature and its azimuth; the U_{xy} of these tables equals $2\ U_{xy}$ of Eötvös' original practice in station calculations.

[4]H. Haalck, "En graphisches Verfahren für Drehwagenmessungen zur Berechnung der Geländewirkung und der Wirkung beliebig gestalteter Massenkorper," *Zeitschrift für Geophysik*, Heft 4 (1928), S. 161-78.

[5]C. A. Heiland, "A New Graphical Method for Torsion Balance Topographic Corrections and Intepretations," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 1 (January, 1929).

[6]D. C. Barton, "Graphical Terrane Correction for Gravity Gradients," *U. S. Bur. Mines. Tech. Paper 444* (1929).

Those graphical methods were devised to supersede the rather tedious second degree algebraic formulae for the calculation of the terrane effects where the topography within effective distance of the instrument deviates more than a few decimeters from the level of the base of the instrument. Those graphical methods are powerful and flexible and can be used to calculate the gradient and differential curvature produced by irregular terrane of heterogeneous specific gravity. In view of the complication of the task in calculating those effects in a region of rough irregular relief and heterogeneous specific gravity, those graphical methods are rapid and easy, but actually they are rather tedious. For the purposes of most routine commercial surveys, the specific gravity may be assumed to be constant within an octant or within a $22\frac{1}{2}^\circ$ sector; and a sectorial zone of the terrane may be considered to be represented by a flat-topped curvilinear prism whose height (or depth) is determined by an observation of the elevation at one point, or taken as the mean elevation of the sectorial zone. It is then possible to replace the separate graphical charts for gradient and differential curvature by a single simple compact table applicable for all distances from the instrument from *n* units to infinity. A similar table can be devised for the extra-terrane effects produced by an infinitely long railroad embankment or ditch. Tables of this type may be used to calculate the gradient or differential curvature produced by anomalous subsurface masses.

Table I for the terrane effects by octants is based on the division of the area around an instrument into octants whose axes coincide with the N., NE., E., SE., S., SW., W., and NW. radii. The octants are divided into zones by concentric circles of radii respectively 5, 11, 23, 50, 110, 230, 500, 1,100, 2,300, 5,000 units (feet, yards, meters) (see Fig. 1). This spacing of the circles is so chosen that the radius of each circle is $\sqrt[3]{10}$ times the radius of the next smaller circle, and that the radius of the *n*th circle from the circle of 5 units' radius is $5\sqrt[3]{10^n}$.

The 5 to 11 zone is split into a series of curvilinear prisms whose heights differ successively by 0.1 unit (feet, yards, meters), and whose common base lies in the horizontal plane through the center of gravity of the instrument (Fig. 2). The gradient produced by each prism was calculated by Nikiforov's formula for cylindrical coördinates with the origin at the center of gravity of the torsion balance, and the differential curvature was calculated by the parallel formula,

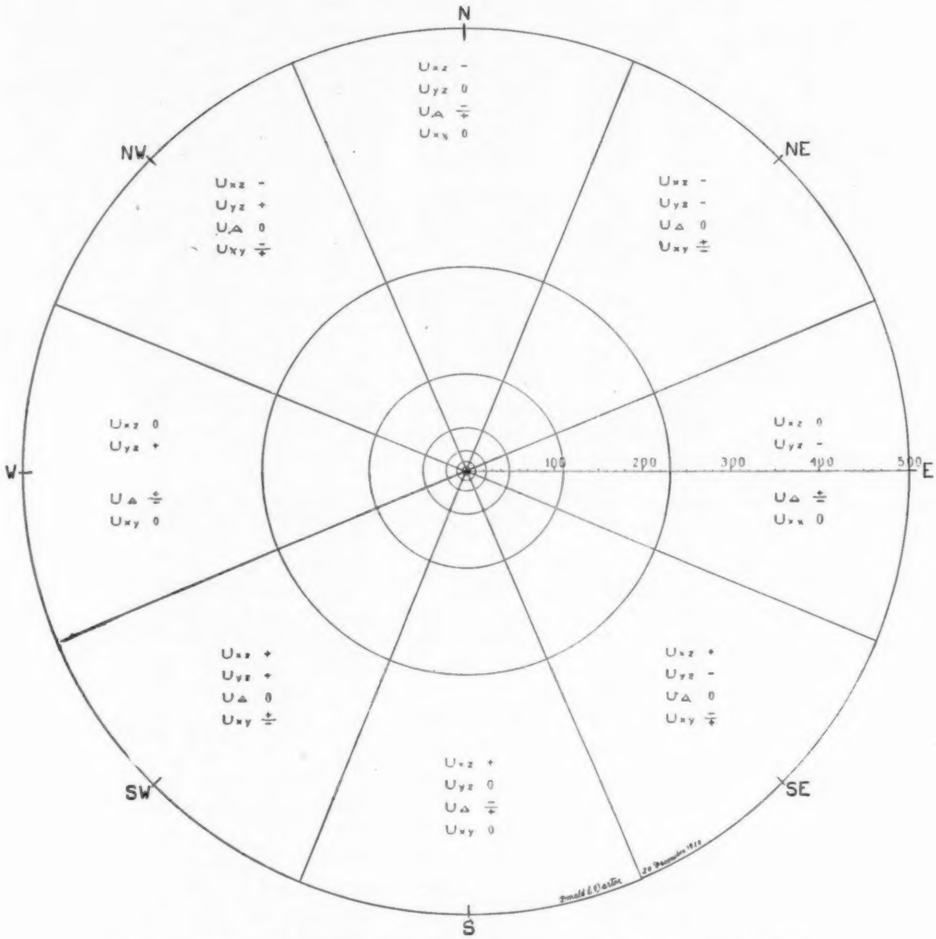


FIG. 1.—Plan of template showing division of terrane by octants and by zones of $5\sqrt[3]{10^n}$ radius.

TABLE I

TABLE OF TERRANE EFFECTS BY OCTANTS FROM 5 UNITS (FEET, YARDS, METERS) TO INFINITY

TABLE OF TERRANE EFFECTS

ELEVATIONS: ZONES 5 to 11 (5(0), 5(00))	11 to 23 (11(0), 11(00))	23 to 50 (23(0), 23(00); 50(0), 50(00))	EFFECTS: OCTANTS N·S U_{xz} / E·W U_{yz}	NE, SE, SW, NW U_{xz} & U_{yz}	N, S, E, W U_Δ / NE, SE, SW, NW U_{xy}
+2.00	+4.31	+9.28	−4.28E	−3.02E	−28.2E
1.90	4.09	8.82	−3.90	−2.76	−27.0
1.80	3.88	8.36	−3.54	−2.50	−25.7
1.70	3.66	7.89	−3.18	−2.25	−24.4
1.60	3.45	7.43	−2.85	−2.01	−23.1
1.50	3.23	6.96	−2.52	−1.78	−21.8
1.40	3.02	6.50	−2.28	−1.61	−20.4
1.30	2.80	6.03	−1.92	−1.36	−19.1
1.20	2.59	5.57	−1.64	−1.16	−17.7
1.10	2.37	5.11	−1.40	− .99	−16.3
1.00	2.45	4.64	−1.16	− .82	−14.8
.90	1.94	4.18	−.95	− .67	−13.4
.80	1.72	3.71	−.75	− .53	−12.0
.70	1.51	3.25	−.58	− .41	−10.5
.60	1.29	2.79	−.43	− .30	− 9.0
.50	1.08	2.32	−.30	− .21	− 7.5
.40	.86	1.86	−.19	− .14	− 6.0
.30	.64	1.39	−.11	− .08	− 4.5
.20	.43	.93	−.05	− .03	− 3.0
+.10	+ .22	+ .46	−.02	− .01	− 1.5
0 Center of Gravity of Torsion Balance					
−.10	− .22	− .46	−.02	− .01	+ 1.5
.20	.43	.93	−.05	− .03	+ 3.0
.30	.64	1.39	−.11	− .08	+ 4.5
.40	.86	1.86	−.19	− .14	+ 6.0
.50	1.08	2.32	−.30	− .21	+ 7.5
.60	1.29	2.79	−.43	− .30	+ 9.0
.70	1.51	3.25	−.58	− .41	+10.5
.80	1.72	3.71	−.75	− .53	+12.0
.90	1.94	4.18	−.95	− .67	+13.4
1.00	2.15	4.64	−1.16	− .82	+14.8
1.10	2.37	5.11	−1.40	− .99	+16.3
1.20	2.59	5.57	−1.64	−1.16	+17.7
1.30	2.80	6.03	−1.92	−1.36	+19.1
1.40	3.02	6.50	−2.28	−1.61	+20.4
1.50	3.23	6.96	−2.52	−1.78	+21.8
1.60	3.45	7.43	−2.85	−2.01	+23.1
1.70	3.66	7.89	−3.18	−2.25	+24.4
1.80	3.88	8.36	−3.54	−2.50	+25.7
1.90	4.09	8.82	−3.90	−2.76	+27.0
−2.00	−4.31	−9.28	−4.28	−3.02	+28.2

These Effects are for Specific Gravity 1.0

Donald C Barton 20 December 1928

RULE OF SIGNS

Multiply Sign of Effect by

Octant	U_{xz}	U_{yz}	U_Δ	U_{xy}
N	+	0	+	0
NE	+	+	0	−
E	0	+	−	0
SE	−	+	0	+
S	−	0	+	0
SW	−	−	0	−
W	0	−	−	0
NW	+	−	0	+

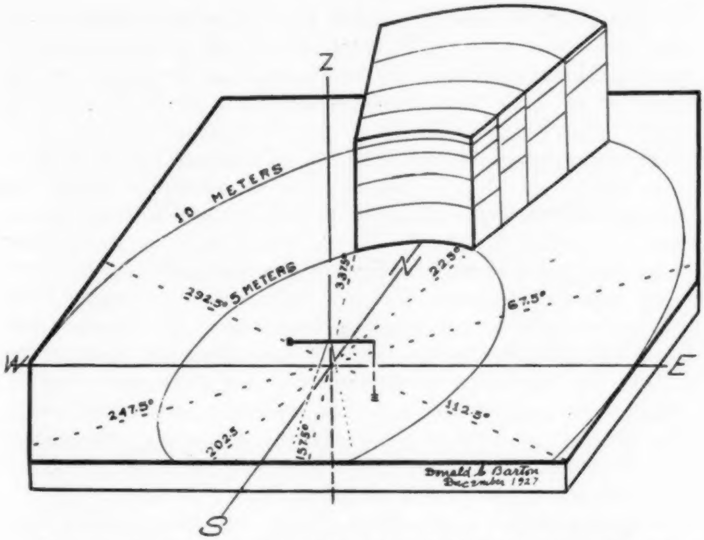


FIG. 2.—Diagrammatic representation of the division of the terrane by octants, zones, and vertical prisms. The prisms of each zone differ by 0.1 E effect.

$$U_{xz} = K\delta \; (\sin \alpha_{m+1} - \sin \alpha_m) \left[\frac{\rho_{n+1}}{r_{n+1}} - \frac{\rho_n}{r_n} + \log_e \frac{\rho_{n+1}}{\rho_n} \left(\frac{\rho_n + r_n}{(\rho_{n+1} + r_{n+1})} \right) \right]$$

where $r^2 = \rho^2 + Z^2$

$$U_\Delta = K\delta \frac{1}{2} (\sin 2\alpha_{m+1} - \sin 2\alpha_m) \left[\frac{Z}{r_n} - \frac{Z}{r_{n+1}} + 2\log \frac{\rho_{n+1}}{\rho_n} \left(\frac{Z + r_n}{Z + r_{n+1}} \right) \right]$$

where $r^2 = \rho^2 + Z^2$

The 11 to 23 zone is divided into a similar series of prisms, differing in height by $\sqrt[3]{10}$. The mth prism of this series will have the dimensions $\rho = 5\sqrt[3]{10}$ to $5\sqrt[3]{10^2}$ and $Z = 0$ to $m\sqrt[3]{10}$ which are $\sqrt[3]{10}$ times ($\rho = 5$ to $5\sqrt[3]{10}$ and $Z = 0$ to m). The latter are the dimensions of the mth prism in the 5 to 11 zone; that is, each prism of the 11 to 23 is an exact projection of a prism of the 5 to 11 zone, and the gradient (or differential curvature) effect of the respectively corresponding prisms is the same.

Each successive zone is split into a similar series of prisms, whose respective dimensions are $\sqrt[3]{10}$ times the equivalent dimensions of the prisms of the next inner zone. In the nth zone from the 5 to 11 zone, the dimensions are $\sqrt[3]{10^n}$ times the dimensions of the prisms of the 5 to 11 zone.

If the n zones, 5 to 11, (5 to 11) $\sqrt[3]{10}$ = (11 to 23), (5 to 11) $\sqrt[3]{10^2}$ = (23 to 50), * * * * (5 to 11) $\sqrt[3]{10^n}$ are considered, then all the prisms of the respective heights: m in the first zone, $m\sqrt[3]{10}$ in the second, $m\sqrt[3]{10^2}$ in the third, * * * * and $m\sqrt[3]{10^n}$ in the nth zone produce the same gradient (or differential curvature) effect at the origin. By the choice of the factor $\sqrt[3]{10}$, the dimensions of the second three zones are 10 times the corresponding dimensions of the respective first three zones; the dimensions of the third three zones are 100 times the corresponding dimensions of the respective first three zones, that is, [5 to 11, 11 to 23, 23 to 50] [50 to 110, 110 to 230, 230 to 500] [500 to 1,100, 110 to 2,300, 2,300 to 5,000] et cetera. By proper consideration of the decimal point, it is possible to use the first three zones, 5 to 11, 11 to 23, and 23 to 50, for all zones out to infinity.

For the north and south octants, U_{yz} and U_{xy} are zero; and for the east and west octants U_{xz} and U_{xy} are zero.

For the northeast, southeast, southwest, and northwest quadrants, U_Δ is zero, and $U_\Delta{}'$ becomes U_{xy}; and U_{yz} and $U_{xz} = 0.707 \times U_{sz}$.[1]

Table I was composed by tabulating in the first column the elevations in the 5 to 11 zone by 0.1 unit (feet, yards, meters) from 0 to ±2.0; in the second column the corresponding elevations in the 11 to 23 zone; in the third column the corresponding elevations in the 23 to 50 zone; in the fourth column, the corresponding gradient effects for the north, east, south, or west quadrants; in the fifth column, corresponding gradient effects for the northeast, southeast, southwest, and northwest quadrants; and in the sixth column, the corresponding differential curvature effects, U_Δ in the north, east, south, and west quadrants, and U_{xy} in the northeast, southeast, southwest, and northwest quadrants.

The reasons for the rules of sign given in the table can be visualized by remembering

> That the origin of the system and point to which elevations are referred is the center of gravity of the balance and not the base of the instrument.
>
> That a positive mass above, or a negative mass below the level of the origin, and on the north (east) of it produces a negative gra-

[1] U_{sz} and $U_\Delta{}'$ refer respectively to the component of the gradient and the differential curvature value along, and referred to, the axis of the octant or 22½°-sector.

dient, that is, a positive or a negative elevation in the north (east) half of the area produces a $'-U_{xz}$ $(-U_{yz})$.

That the sign is reversed if the mass is south (west) of the origin.

That an anomalous positive mass in the north quadrant produces a $-U_\Delta$, whether the mass is above or below the origin, and a negative mass produces a $+U_\Delta$, no matter whether the mass is above or below the origin; that is, a positive elevation gives a $-U_\Delta$ and a minus elevation gives a $+U_\Delta$.

That for the northeast quadrant and for a mass above (below) the origin, $U_\Delta{}'$ is $-$ $(+)$ and with the transformation of coördinates from NE.-SW., NW.-SE. to N.-S., E.-W., $-$ $(+)$ $U_\Delta{}'$ becomes $+(-)U_{xy}$. The transformation is understood most easily if it is performed graphically.

That for the differential curvature, anomalies of mass similarly placed in opposite octants produce effects of like sign, but in octants 90° apart, produce effects of opposite sign.

The easiest handling of the signs is to neglect them in taking the effect from the table and to use a scratch pad form such as that given in Figure 3, in which the signs are automatically taken care of. Such a scratch pad form serves to provide a record of the calculations for future checking.

In the use of these tables:

The elevations can be taken at distances of 5, 11, 23, 50 * * * units (feet, yards, meters) and the mean elevation for each zone used, but it is more accurate to take them at distances of 7.3, 16, 34 * * * units (feet, yards, meters).

The elevations used are those above or below the level of the center of gravity of the torsion balance.

If the H. I of the level is made the same as the elevation of the center of gravity of the torsion balance, the levels read may be used directly.

The height of the center of gravity of the torsion balance above the ground is immaterial, as long as the elevations of the zones fall within the table.

The units of measurement preferably should be meters or yards. To use feet as the unit of measurement, the numerical value of the elevations in the first three columns and of the radial distances of the zones should be multiplied by 3.

The calculations of the terrane effects must be carried out to equal distances in opposite octants for the gradient or to equal dis-

tances in pairs of octants at 90° to each other for the differential curvature, but preferably should be carried out in each octant until the effect is negligible.

The respective values for the gradient and differential curvature determined by the use of the table must be multiplied by the mean specific gravity of subsoil.

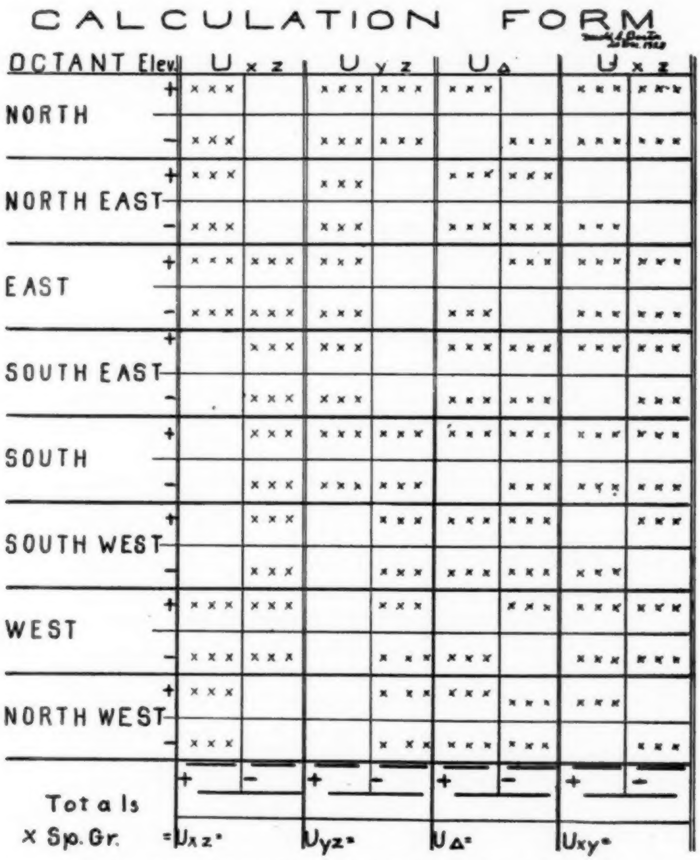


FIG. 3.—Suggested scratch pad form for calculations with Table I.

According to the rule of signs given, the values obtained from this table are effects and not corrections and, therefore, are to be subtracted algebraically from the observed values.

TABLE II

TABLE OF TERRANE EFFECTS FOR INFINITE STRAIGHT DITCH OR EMBANKMENT

TABLE OF TERRANE EFFECTS

ZONES — 22½° SECTORS

Zones: 5.0 (50) (500) — 7.3 (73) (730) — 10.8 (108) (1080) — 15.9 (159) (1590) — 23.2 (232) (2320) — 34.1 (341) (3410) — 50 (500) (5000)

Sectors: U_{xz} and U_{yz}: I, II, III, IV; U_Δ and U_{xy}: V, VI

ELEVATIONS						EFFECTS I	II	III	IV	V	VI
.10	.15	.22	.32	.46	.68	.01	.01	.00	.00	.49	.34
.20	.29	.43	.63	.93	1.36	.02	.02	.01	.01	.98	.69
.30	.44	.64	.95	1.39	2.04	.05	.04	.03	.02	1.46	1.03
.40	.59	.86	1.27	1.86	2.73	.06	.06	.04	.02	1.94	1.37
.50	.73	1.08	1.58	2.32	3.41	.10	.09	.07	.04	2.42	1.71
.60	.88	1.29	1.90	2.79	4.09	.14	.13	.10	.06	2.90	2.05
.70	1.03	1.51	2.21	3.25	4.77	.20	.19	.14	.08	3.37	2.38
.80	1.17	1.72	2.53	3.71	5.45	.25	.24	.18	.10	3.84	2.71
.90	1.32	1.94	2.85	4.18	6.13	.32	.30	.23	.12	4.30	3.04
1.00	1.47	2.15	3.16	4.64	6.81	.39	.36	.28	.15	4.75	3.36
1.10	1.62	2.37	3.48	5.11	7.49	.47	.44	.33	.18	5.20	3.68
1.20	1.78	2.59	3.80	5.57	8.18	.55	.51	.39	.21	5.65	3.99
1.30	1.91	2.80	4.11	6.03	8.86	.64	.60	.45	.25	6.08	4.30
1.40	2.06	3.02	4.43	6.50	9.54	.74	.69	.52	.28	6.51	4.31
1.50	2.20	3.23	4.74	6.96	10.22	.84	.78	.59	.32	6.93	4.90
1.60	2.35	3.45	5.06	7.43	10.30	.94	.88	.67	.36	7.35	5.19
1.70	2.50	3.66	5.38	7.89	11.58	1.06	.98	.75	.40	7.75	5.48
1.80	2.64	3.88	5.69	8.36	12.26	1.17	1.09	.83	.45	8.15	5.78
1.90	2.79	4.09	6.01	8.82	12.94	1.28	1.20	.91	.49	8.53	6.03
2.00	2.94	4.31	6.37	9.28	13.63	1.41	1.31	.99	.54	8.91	6.30

Donald C. Barton
20 December 1927

KEY: A- For + Elevations

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
U_{xz}	-I	-II	-III	-IV	0	+IV	+III	+II	+I	+II	+III	+IV	0	-IV	-III	-II
U_{yz}	0	-IV	-III	-II	-I	-II	-III	-IV	0	+IV	+III	+II	+I	+II	+III	+IV
U_Δ	-V	-VI	0	+VI	+V	+VI	0	-VI	-V	-VI	0	+VI	+V	+VI	0	-VI
U_{xy}	0	+VI	+V	+VI	0	-VI	-V	-VI	0	+VI	+V	+VI	0	-VI	-V	-VI

B- For − Elevations

U_{xz} U_{yz} Use the same signs as in A

U_Δ U_{xy} Change the signs in A

This Table is for Specific Gravity 1.0

Table II is entirely similar to Table I in construction, but 22½° sectors are used instead of octants, and the space between 5 and 50 is divided into six zones instead of three (Fig. 4). Any dimension of any zone, therefore, is $\sqrt[6]{10}$ times the corresponding dimension of the next inner zone. For the NNE., NNW., SSE., and SSW. (ENE., ESE., WSW., WNW.) sectors, and without regard to sign, U_{xz} (U_{yz}) = U_{sz} *cos* (*sin*) 22½°; U_{xz} (U_{yz}) = U_{sz} *sin* (*cos*) 22½°; $U_\Delta = U_\Delta' \cdot \cos 2(22½°) = U_\Delta' \cos 45°$; and $U_{xy} = U_\Delta' \sin 45°$. The values respectively

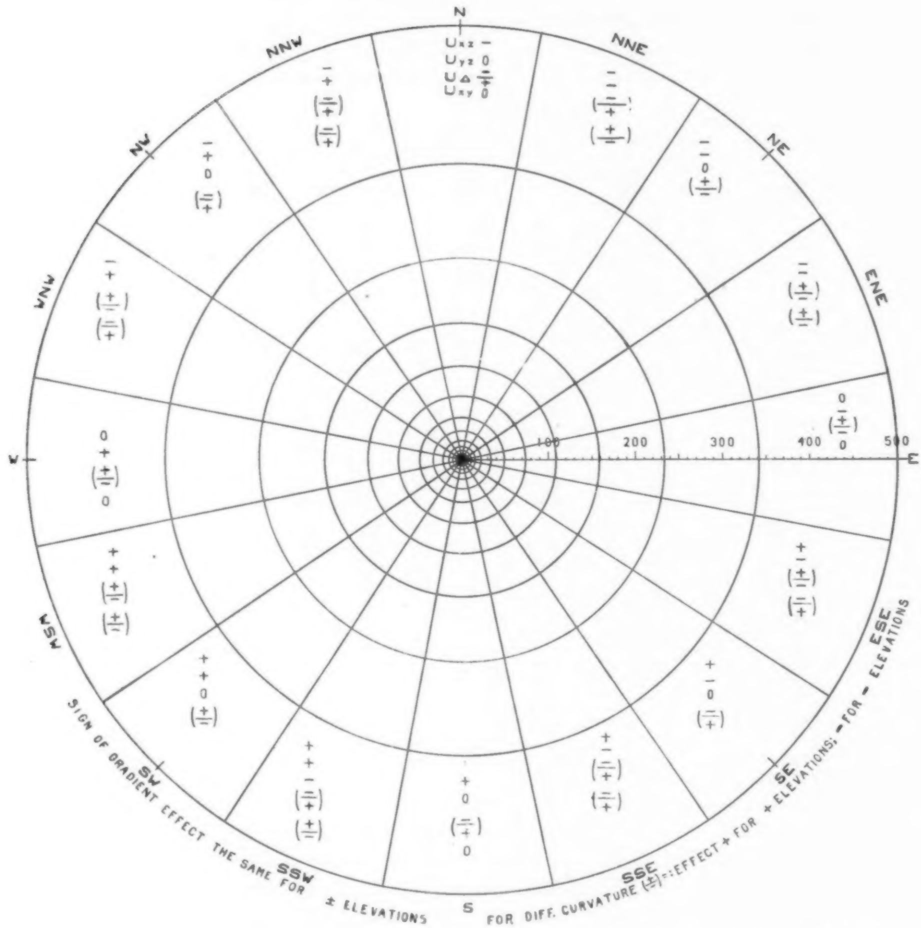


FIG. 4.—Plan of template showing division of terrane by 22½° sectors and by zones of $5\sqrt[6]{10^n}$ radius.

for U_{xz} and U_{yz} and for U_Δ and U_{xy} for those sectors are each tabulated in a column in addition to the respective columns for the N., E., S., and W. sectors and for the NE., SE., SW., and NW. sectors. The use of the table is the same as for Table I.

If the three columns for the gradient (*I*, *II*, *III*) and the two for the differential curvature (*IV* and *V*) prove confusing to anyone, he may find it more convenient to drop columns *II*, *III*, and *V* and obtain U_{sz} and U_Δ' for each sector and its opposite sector and then to multiply by the appropriate factor as follows.

TABLE III

Sector	U_{xz}	U_{yz}	U_Δ	U_{xy}
N.	−1	0	−1	0
NNE.	−0.924	−0.383	−0.707	+0.707
NE.	−0.707	−0.707	0	+1
ENE.	−0.383	−0.924	+0.707	+0.707
E.	0	−1	+1	0
ESE.	+0.383	−0.924	+0.707	−0.707
SE.	+0.707	−0.707	0	−1
SSE.	+0.924	−0.383	−0.707	−0.707
S.	+1	0	−1	0
SSW.	+0.924	+0.383	−0.707	+0.707
SW.	+0.707	+0.707	0	+1
WSW.	+0.383	+0.924	+0.707	+0.707
W.	0	+1	+1	0
WNW.	−0.383	+0.924	+0.707	−0.707
NW.	−0.707	+0.707	0	−1
NNW.	−0.924	+0.383	−0.707	−0.707

A scratch pad calculation form similar to that of Figure 3 can profitably be made up either for use with columns *II*, *III*, and *V*, or with the use of columns *I* and *IV* and the subsequent multiplication with the proper factor from Table IV.

If the subdivision of horizontal space used in the construction of Table III is not sufficiently fine,

A. The right and left halves of each sector may be used independently. The value read from the table must then be divided by 2.

B. Each 22½°-zone may be split into two subzones in such a way that the radial width of the inner zone is ⅓, and of the outer zone is ⅔, of the radial width of the zone. The value read from the table must then be divided by 2.

C. The double subdivision of the 22½° sectorial zone, both according to "*A*" and "*B*," may be used. In that case, the values read from the table must be divided by 4.

Table IV is similar to Table I, but gives the effects from 0 to 2.3 by octants. The common top of the series of prisms is assumed to be at 0.7 instead of at 0. The effects of the prisms from 0 to 0.7 cancel out on account of the balanced equal effects of opposite sign around the origin.

For the effects from 2.3 to 5, either Table I or Table III may be used.

If the elevations for use in making the terrane correction have to be taken from a topographic map, templates on thin celluloid and drawn like Figure 1 or Figure 4 are convenient to use. If the drafting is on the lower side, and the upper side is faintly roughened with sand paper, the elevation for each zone may be written directly on the template.

In estimating the elevation to be used for each zone, it should be remembered that if there is considerable effective variation of elevation in a zone,

A. The use of the mean elevation introduces a considerable percentage of error in the value for the gradient.

B. The use of the mean elevation introduces a lesser but considerable percentage of error in the value for the differential curvature, if the elevations or depressions subtend a considerable angle at the origin.

C. The use of the mean elevation introduces no appreciable error in the value for the differential curvature if the elevations or depressions subtend only a small angle from the horizontal.

D. In *A* and *B*, instead of using the mean elevation for a zone, it is preferable approximately to estimate that weighted "*m*" per cent of the zone has an elevation of "*a*" feet, and weighted "*n*" per cent an elevation of "*b*" feet; if E_a and E_b are the effects corresponding respectively with elevations of "*a*" and "*b*," the effect of the zone is $mE_a + nE_b$. In estimating the weighted proportioning of the zone, it should be remembered that an inner radial ⅓ and an outer radial ⅔ have equal effects.

E. If a single determination is made of the elevation of a zone, it should be taken approximately 0.4 of the radial width of the zone out along the radial axis for surfaces sloping toward the origin, 0.35 out for horizontal surfaces, and 0.3 out for surfaces sloping away from the instrument.

The differential curvature, more quickly than the gradient, becomes unusable with increasing roughness of topographic relief and the col-

TABLE IV

TABLE OF TERRANE EFFECTS FROM 0 TO 2.3

TERRANE CORRECTION TABLE
By OCTANTS from 0 to 2.3

ELEV. 0 to 2.3	Uxz & N,S,E,&W Octants	Uyz NE,SE,SW &NW Octs.	U△ & Uxy
.70	0.00	0.00	0.0
.75	0.45	0.32	1.3
.80	0.94	0.66	2.6
.82	1.13	0.80	3.1
.84	1.33	0.94	3.6
.86	1.54	1.09	4.2
.88	1.75	1.24	4.7
.90	1.97	1.39	5.3
.92	2.18	1.54	5.8
.94	2.41	1.70	6.3
.96	2.64	1.87	6.8
.98	2.87	2.03	7.3
1.00	3.09	2.18	7.8
1.02	3.33	2.35	8.8
1.06	3.79	2.68	9.4
1.08	4.02	2.84	9.9
1.10	4.27	3.02	10.3
1.12	4.50	3.18	10.9
1.14	4.73	3.34	11.3
1.16	4.97	3.51	12.3
1.20	5.47	3.87	12.8
1.22	5.73	4.05	13.3
1.24	6.00	4.24	13.8
1.26	6.27	4.43	14.3
1.28	6.53	4.62	14.7
1.30	6.81	4.81	15.2

umns for differential curvature in Tables I and III become superfluous. There is therefore a slight advantage in recasting the table so that the effects are not given for successive 0.1 units (feet, yards, meters) of elevation in the 5 to 11 (or 5 to 7.3) zone, but that elevations are given for each 0.1 *E* difference of effect.

The gradient and differential curvature produced by subsurface bodies may be calculated by the use of Tables I, II, and IV, if the depths to be used be within the range of the tables. But as those tables are designed specifically for the purpose of calculating terrane effects, they are constructed for use only with elevations or depths subtending an angle from the horizontal of less than 15° at the origin. If the tables such as I, II, and IV are to be used to calculate the gradient and differential curvature produced by subsurface bodies, (*a*) either the tables equivalent to Tables I and II should be constructed separately for the gradient and differential curvature and the elevations corresponding with each 0.1 *E* or (0.2, 0.5 or 1 *E*) increase in effect should be tabulated opposite their respective effects, or (*b*) if the gradient differential curvature effects are both used, a different spacing interval of depths should be used at different depths. The tables in either case should be carried down to infinity.

The method of calculation is to sketch the structure contours of the anomalous mass, to construct a template of the type of Figures 1 and 4, and then proceed in the same manner as if the structure contours were topographic contours. If the anomalous mass has a finite thickness, the structure contours must be drawn for both the top and the bottom. The elevations for the top and for the bottom in each zone must be looked up simultaneously in the table and the differences in the effects taken.

This method of calculation of the gradient and differential-curvature effects of anomalous subsurface masses is particularly adapted for the general case of the calculations of the effects of an irregular surface on the basement, or on an enormously thick formation, or the effects of an irregularly warped bed, and is equally applicable for all points on irregular structure. The method will handle situations of heterogeneous density. The method relatively is rapid and simple compared with the other methods, but is tedious. In the reverse calculation of unknown masses from observed effects, its use requires a rather high power of visualization in three dimensions. For the special case of the gradient or differential curvature along axes of symmetry across a structure, the writer, Haalck, and others have suggested a graphical

TABLE V

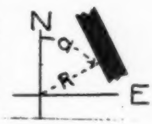
TABLE OF TERRANE EFFECTS BY $22\frac{1}{2}°$ SECTORS AND BY ZONES OF $5\sqrt{10^n}$ RADIUS FROM 5 TO INFINITY

TERRANE CORRECTION TABLE
INFINITE DITCH or EMBANKMENT

DISTANCES & ELEVATIONS in TERMS of R=100

ZONES

100	110	121	133	146	161	177	Usz
ELEVATIONS							E
40	44	48	53	58	65		0.7
37	40	44	49	54	59		0.6
33	36	40	44	48	53		0.5
29	32	35	39	43	47		0.4
25	28	30	34	37	41		0.3
20	22	25	27	30	33		0.2
14	16	17	19	21	23		0.1
							U△′
37	41	45	50	55	60		4.0
32	35	38	42	46	51		3.5
26	29	32	35	39	43		3.0
22	24	26	29	32	62		2.5
17	19	21	23	25	27		2.0
13	14	15	17	18	20		1.5
8	9	10	11	12	13		1.0
4	4	5	5	6	6		0.5



$$U_{xz} = U_{sz} \cos a$$
$$U_{yz} = U_{sz} \sin a$$
$$U_{\Delta} = -U_{\Delta'} \cos 2a$$
$$U_{xy} = U_{\Delta'} \sin 2a$$

method which is very much more rapid and simpler, which can be handled by an intelligent clerk, and which handles certain types of complex density situations more easily than the method using the tables. A wide range of structures in which the geologist or geophysicist is interested may have a vertical axial plane of symmetry, as a moderate difference in the length of a prism at right angles to the axial plane has a negligible effect on the gradient or differential curvature; and the larger portion of the purposes of the geologist and geophysicist will be satisfied by the knowledge of the structural relations along an axis of sym-

metry and a map showing the symmetry of the structure. If much calculation along such axes of symmetry is to be done, time will be saved by construction and use of such graphical charts, but they are not applicable for positions off axes of symmetry. For such positions, the method of these tables or one of the more or less similar graphical methods should be used. These tables have the advantages that one set of tables is universally applicable, and if only a small amount of calculation is to be done for positions on axes of symmetry, it may be simpler and less time-consuming to use the tables.

For the use of Tables I and II in regions where the relief above or below the instrument is more than 15 per cent of the distance from the instrument, it would be necessary to calculate an extension of Tables I and II by the use of formulae 1 and 2.

Table V is designed for the calculation of gradient and differential curvature effects of a very long essentially straight embankment or ditch. To make a compact table applicable for any distance from the instrument, the perpendicular distance to the embankment or ditch is assumed to be 100; all measured distances and elevations, therefore, must be divided by $\frac{1}{100}$ of that perpendicular distance to the nearest edge of the embankment or ditch.

The values then obtainable from the table are the U_{sz} and U_{Δ}' along that perpendicular. U_{sz} and U_{Δ}' must be resolved respectively into U_{xz}, U_{yz}, and U_{Δ}, U_{xy} by the formulae making use of the angle of azimuth of that perpendicular to the embankment or ditch, that is,

$$
\begin{aligned}
U_{xz} &= U_{sz} \cos \alpha \\
U_{yz} &= U_{sz} \sin \alpha \\
U_{\Delta} &= U_{\Delta}' \cos 2\alpha \\
U_{xy} &= U_{xy}' \sin 2\alpha
\end{aligned}
$$

where α is the azimuth of the perpendicular to the ditch or embankment measured clockwise from the north.

OIL FIELDS AND STRUCTURE OF SWEETGRASS ARCH, MONTANA[1]

THOMAS B. ROMINE[2]
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ABSTRACT

The oil fields of the Sweetgrass arch are so situated geographically that their development has been unaffected by the general depression of the oil business during the past two years. For this reason there has been considerable activity and attempts have been made, and are being made, to locate new pools.

The oil in the Sweetgrass arch fields occurs locally on minor folds on the arch, and the greater part of the production is at the top of the Madison limestone (Mississippian). Productivity is determined largely by the existent porosity at the top of the Madison.

Large areas on the Sweetgrass arch remain untested, especially those in which surface structure is obscured by glacial drift. Such areas are worthy of intelligent prospecting in an attempt to locate local structures.

INTRODUCTION

The Sweetgrass arch comprises a large area in north-central Montana, which extends northward from Great Falls to the Canadian border and eastward from Pendroy to Fort Benton. The oil fields on the arch, the Kevin-Sunburst, Pondera, and Bannatyne, lie within a radius of 75 miles of the international boundary, and are the most northerly oil fields in the United States (Fig. 1).

This geographic position has been favorable to the development of the Sweetgrass arch oil fields, because the operators have been able to market their production locally without competition from other oil fields of the Rocky Mountain region. During the past two years of depression due to over-production, the price of Kevin-Sunburst crude has suffered no cut. On the contrary, during the spring and summer of 1928 the price was advanced twice, a total of 30 cents per barrel.

The price of Kevin-Sunburst crude, the past two years, has given considerable encouragement to development in the Sweetgrass arch fields. With the discovery of oil in the Bannatyne and Pondera fields in 1927, some distance from the Kevin-Sunburst field, attention has also been directed to attempts to locate other pools on the Sweetgrass arch.

[1]Read before the Association at the Fort Worth meeting, March 21, 1929. Manuscript received by the editor, February 25, 1929.

[2]Geologist, Texas Pacific Coal and Oil Company.

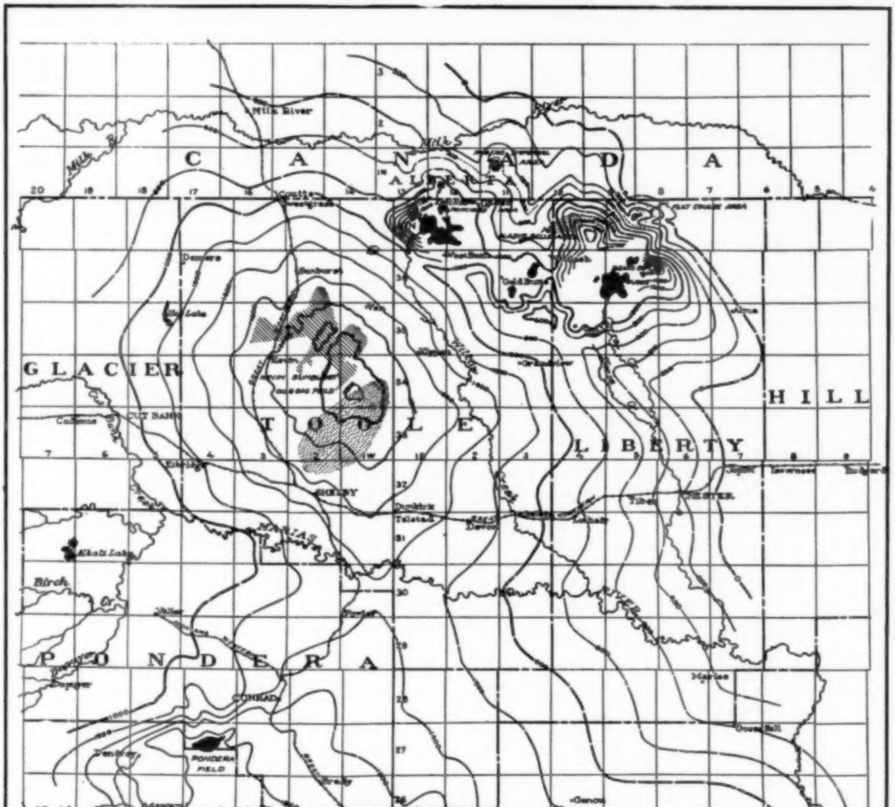
OIL FIELDS AND STRUCTURE
OF THE
SWEETGRASS ARCH
NORTH CENTRAL MONTANA
Scale
Contours on top of Madison Limestone
Interval 200 feet
Datum Mean Sea Level
area of oil production
area of gas production
igneous intrusives & extrusives
CANADA
ALBERTA
GLACIER
TOOLE
LIBERTY
HILL
PONDERA
CHOUTEAU
TETON
LEWIS AND CLARK
CASCADE
JUDITH BASIN
Milk River
Shelby
Conrad
Choteau
Fort Benton
Great Falls
Pondera Field
Cut Bank
Chester
Valier
Dupuyer
Brady
Collins
Vaughn
Sun River
Augusta
Sand Coulee
Belt
Simms
Cascade
Ulm
Portage
Floweree
Carter
Marias
Loma
Devon
Dunkirk
Tiber
Galata
Sweetgrass
Coutts
Kevin
Sunburst
Oilmont
Ethridge
Dupuyer Cr.
Birch Cr.
Muddy Creek
Teton R.
Sun R.
Missouri River
Marias River
Belt Cr.

FIG. 1

In this paper the writer has attempted to set down briefly some notes on the development and status of the oil fields of the Sweetgrass arch, and a brief discussion of the stratigraphy and general structure of the area, with ideas concerning the relation of minor structures to the occurrence of oil.

In the preparation of this paper, use has been made of many data and suggestions gathered from geologists who have made a study of the Sweetgrass arch area. The writer wishes, at this time, to acknowledge with gratitude the kindly assistance of Roy Lebkicher[1] for data on the Paleozoic stratigraphy, for production statistics, and for his reading and criticism of the manuscript. To Wm. T. Nightingale[2] the writer is grateful for many helpful suggestions in regard to the structure of the Sweetgrass Hills area. To V. J. Hendrickson, of the Texas Production Company, and F. C. Platt, Northern Oil Information Bureau, the writer is indebted for many data concerning wells of the Sweetgrass arch.

HISTORY OF DEVELOPMENT

KEVIN-SUNBURST FIELD

The discovery well of the Kevin-Sunburst field was completed in March, 1922, at a depth of 1,770 feet, with an initial production of 20 barrels. Production was encountered in the upper 20 feet of the Madison limestone. This well was located 600 feet down structure on the northwest flank of the Kevin-Sunburst dome. The discovery well was never a commercial producer, because deeper drilling encountered water which resulted in the loss of the well.

The second producing well of the field was located 7 miles northeast of the discovery well. The latter was drilled by the Sunburst Oil and Refining Company and was completed in June, 1922. This well produced 150 barrels daily from the Sunburst sand of the Kootenai (Lower Cretaceous) at a depth of 1,535 feet.

The second well, located on the north flank of the Kevin-Sunburst dome, proved to be 150 feet higher structurally than the discovery well. Following the completion of the Sunburst well, interest centered on the north end of the dome, and practically all subsequent development extended south and southeast.

By the end of the year 1922, 46 wells had been completed in the Kevin-Sunburst field, of which 25 were producing oil wells, 2 were gas

[1]Geologist, The California Company, Great Falls, Montana.

[2]Geologist, The Ohio Oil Company, Casper, Wyoming.

wells, and 19 were dry holes. The total production at the end of the year was 51,000 barrels.

In 1923, development continued south of the Sunburst well and resulted in the discovery of a few wells of large flush production in the area now known as the Baker-Howling pool.

During 1924, the Kevin-Sunburst field received its first real impetus through the discovery of the Queen City pool, located 5 miles south of the Baker-Howling pool. The former yielded several wells whose flush production reached a maximum of 3,000 barrels daily.

In 1925, development continued eastward from the Queen City area and resulted, toward the end of the year, in the discovery of the Rice-Fulton, or East pool, which has been by far the most important discovery in the entire field.

With the development of the East pool and subsequent discovery of the Lashbaugh pool, the Kevin-Sunburst field reached its peak of production in July, 1926. During this month the average daily production was 26,000 barrels, or a total production for the month of 805,000 barrels from 550 producing wells. The annual production for 1926 was 6,480,000 barrels.

In 1927, drilling was confined principally to known producing areas. A few scattered wells with large initial production were found south of the East pool in what are known as the Wilcox and Baker-Barger areas. The production of the field declined rapidly, although 202 oil wells were completed.

During 1928, 114 oil wells and 38 gas wells were obtained from 246 wells drilled. The production in 1928 was 3,174,000 barrels as compared with 4,208,600 barrels in 1927.

From the beginning of development to January 1, 1929, the Kevin-Sunburst field has produced 18,704,360 barrels of oil. Throughout the same period 1,724 wells have been drilled, of which, at present, 938 or 54.4 per cent are producing oil wells, 131 or 7.6 per cent are gas wells, and 655 or 38 per cent are dry holes and abandoned wells. For the month of December, 1928, the average daily production of 938 producing wells was 7.2 barrels.

PONDERA FIELD

The discovery well of the Pondera field was completed by the Montana Pacific Oil Company, in June, 1927, at a depth of 2,060 feet, after having penetrated the Madison limestone to a depth of 22 feet. This well was never commercial, although it encountered a flow of 3,500,000 cubic

feet of gas daily, and a spray of oil from the upper part of the Madison. The oil production of this well was rated at 3 barrels daily.

In March, 1928, the second well of the field was completed by the Fulton Petroleum Company. This well was located ½ mile northeast of the discovery well, and was completed at a depth of 2,040 feet, after having obtained an initial production of 1,000,000 cubic feet of gas and 100 barrels of oil daily from the upper 12 feet of the Madison limestone.

Shortly following the completion of the second well, two wells on the east encountered commercial production, and one well on the west found oil, but not in commercial amounts. The extension of the productive area eastward by the two previously mentioned wells resulted in a drilling campaign of considerable activity, which has continued until the present time.

To February 1, 1929, the total production from the Pondera field amounted to 227,500 barrels, and to that date 89 producing wells were completed within the known area of productivity. The average daily production per well for the month of January, 1929, was 31.41 barrels from 83 wells (average), or a total production for the month of 80,860 barrels.

Within the present defined producing area there have been, to date, no dry holes found in the Pondera. However, some wells have had such small initial production as to be doubtfully commercial.

Whether or not the Pondera field has reached its peak of production, at the present time, is doubtful. The productive area is fairly well outlined, but many locations are undrilled. The intensity of the drilling campaign during 1929 will determine whether or not the Pondera field will exceed its present daily output.

BANNATYNE FIELD

The discovery well of the Bannatyne field was completed July 21, 1927, by the Genou Oil Company. This well found oil in a stray sandstone at the base of the Ellis (Jurassic) at a depth of 1,445 feet. This sandstone, known as the Emrick or Bannatyne sand, had a total thickness of 72 feet, but contained oil only in the upper 30 or 40 feet. The well, after shooting, had an initial production of 30 barrels daily of 26°-gravity black oil.

The discovery well was drilled into the Madison limestone, but sulphur water was encountered. Immediately following the completion of the discovery well, several wells were drilled in the vicinity, but none were successful except an offset to the first well. The year 1927 ended

with 2 producing wells having been completed in the Bannatyne out of 11 wells drilled.

In 1928, 12 wells were drilled on the Bannatyne structure, of which 10 were producers and 2 were dry holes.

The wells in the Bannatyne have been scarcely commercial before shooting, and after shooting range in initial production from 10 to 40 barrels daily. The oil is of lower grade than that of either the Kevin-Sunburst or the Pondera, and its market price is doubtful.

To date there has not been sufficient production developed in the Bannatyne to justify laying a pipe line to the nearest railroad point, a distance of 9 miles. The present potential production from the 12 producing wells is estimated to vary from 150 to 175 barrels daily.

For the discovery and location of the Bannatyne and Pondera fields, credit is given to E. B. Emrick[1] and M. S. Darling.[2]

SWEETGRASS HILLS AREA

Considerable drilling has been done in this territory during the past 7 years, and although several areas with apparently favorable structure have been tested, oil in commercial quantities has not been discovered. Showings of high-gravity oil were encountered in the Flat Coulee structure in a basal sand of the Kootenai. The well, however, failed to be commercial. Showings of oil were also found in the Sunburst sand in a well drilled northeast of West Butte in the Pritchard area. This well, which was drilled for gas, was not a commercial producer.

Commercial amounts of gas have been found north and east of the Sweetgrass Hills. The Bears Den structure has been tested by two wells, both of which encountered gas at the top of the Madison limestone, one of which also found gas in the Sunburst sand. These wells gauged 5,000,000 and 10,000,000 cubic feet daily, respectively. In the Gladys Belle area, north of East Butte, commercial flows of gas have been encountered in 6 wells. This gas has a low rock pressure and is found chiefly in a basal sand of the Colorado shale (Cretaceous). Northeast of West Butte, in the Pritchard area, small flows of gas have been found in two wells in the basal Colorado sand. South of Milk River in T. 1 N., R. 11 W. from the 4th meridian, Alberta, Canada, a well drilled on a small structure by the Rogers-Imperial Oil Company, in 1925, encountered flows of gas in the Bow Island sand (Cretaceous), the Sunburst sand, a stray Ellis sand, and at the top of the Madison limestone. The final

[1]Geologist, The Continental Development Company, Conrad, Montana.

[2]Engineer, The Continental Development Company, Conrad, Montana.

gauge of the well showed an open flow of 50,000,000 cubic feet daily with a shut-in pressure of 1,140 pounds per square inch.

Immediately north of West Butte and across the international boundary, the Imperial Oil Company drilled a well on the Erickson Coulee structure, in 1925. This well encountered gas in the Sunburst sand and in the top of the Madison limestone. The flow of gas obtained in this well measured 8,000,000 cubic feet daily at 450 pounds of rock pressure.

At present the gas reserve of the Sweetgrass Hills area is not marketed. Drilling of other wells is taking place, however, in the Gladys Belle, the Bears Den, and the Rogers-Imperial areas, and an outlet for the gas supply is anticipated in the near future.

STRATIGRAPHY

GENERAL STATEMENT

The surface rocks of the area considered in this paper are, except in a few localities, covered by a mantle of glacial drift of Pleistocene age. This surface covering consists of soil, clay, gravel, and boulders, and ranges in thickness from almost nothing to 300 feet.

The surface rocks, where exposed, range in age from the Montana group of the Upper Cretaceous to the Kootenai of the Lower Cretaceous. Deep wells on the Sweetgrass arch have drilled through the Cambrian and into material which has not yet been definitely classified. The sequence, thickness, and character of the sedimentary rocks of the Sweetgrass arch are shown in Table I.

UPPER CRETACEOUS

MONTANA GROUP

Two Medicine formation.—This formation, described first by Stebinger,[1] occupies the west, north, and east flanks of the Sweetgrass arch, and surrounds the Sweetgrass Hills.

The Two Medicine is a fresh or brackish-water formation consisting of more than 1,900 feet of greenish-gray clay and clay shale with irregular lenses of concretionary sandstone. Near the top and near the base there are thin seams of lignite.

This formation contains the Judith River beds of central and eastern Montana, and at its base probably includes a fresh- or brackish-water phase of the marine Claggett formation. The Two Medicine formation is equivalent to the Belly River series of southern Alberta.

[1]Eugene Stebinger, "Possibilities of Oil and Gas in North-Central Montana," *U. S. Geol. Survey Bull. 641-C* (1917).

TABLE I

GEOLOGIC SECTION, SWEETGRASS ARCH, MONTANA

System	*Series*	*Group and Formation*		*Thickness in Feet*	*Character of Rocks*
Quaternary	Recent	Alluvium			Sand, gravel, and silt along larger drainage courses
	Pleistocene	Glacial drift		0–200	Clay, gravel, boulders, and silt
		Unconformity			
Cretaceous	Upper	Montana	Two Medicine formation	1,900+	Gray and greenish-gray clay and shales with irregular lenses of concretionary sandstone. Locally, lignite beds near base
			Eagle sandstone	200–385	Gray to buff massive sandstone containing iron concretions near top and locally a magnetite sandstone bed. Lower part, platy gray sandstone and sandy shale
		Colorado	Colorado shale (Blackleaf member)	1,700–1,850	Gray to black marine shale with thin beds of calcareous concretions and a few thin sands in upper 1,000-1,100 feet. Lower 700-750 feet known as Blackleaf member; contains sandstones, interbedded with dark siliceous shales, clay, and bentonite. Locally, colored shales 400 feet above base
	Lower	Kootenai formation		300–500	Red, green, yellow, and dark gray sandy clay shales with irregular lime and sandstone lenses. Sunburst sandstone member near base
Jurassic	Upper	Ellis formation		150-300	Gray to dark gray and green calcareous shale with locally 1-3 sand lenses near base. Basal part contains much pyrite and locally glauconite
		Unconformity			
Carboniferous	Lower Mississippian	Madison limestone		1,000±	Upper 700 feet chiefly white to cream-colored massive crystalline limestone, locally dolomitic and porous in upper 150 feet. Lower 300 feet thinner-bedded, gray to dark gray and brown limestone with alternating beds of gray and dark gray shale
Devonian	Upper	Three Forks formation		320±	Upper 100 feet very fine-grained calcareous sandstone, black organic shale, and gray calcareous shale, bearing pyrite. Lower 220 feet white to pinkish-colored massive anhydrite with thin laminae of black calcareous shale
	Middle and Lower	Jefferson limestone		540±	Granular, brown, magnesian limestone with varying amounts of white anhydrite. Locally, small flows of carbon dioxide gas under high pressure and slight showings of oil 350 feet below the top
		Unconformity			
Cambrian	Upper and Middle	?		1,400+	1. Upper 500 feet, dense gray to black limestone 2. Middle 700 feet, chiefly gray-green, brown, red, and blue shales with a few beds of limestone 3. Lower member, sandstone and quartzite
		Undetermined			

Eagle sandstone.—The Eagle sandstone forms the rim northwest and west of the Kevin-Sunburst dome, and is likewise a ridge-former along practically the entire west side of the arch as far south as the Sun

River valley. East of the Sweetgrass arch, the Eagle sandstone appears only in isolated outcrops, the most notable being the buttes at Genou.

The Eagle formation differs in thickness from the Sweetgrass Hills toward the southwest. At the former locality the thickness is approximately 200 feet, and 10 miles west of Conrad the average thickness is nearly 385 feet.

The character of the Eagle on the west side of the Sweetgrass arch is unmistakable. The upper part consists of massive gray sandstone containing ironstone concretions, which weather into weird mushroom-like remnants. From the area west of Conrad southward to Choteau the top of the Eagle is capped by a hard, dark-colored bed of magnetite sand. The lower part of the Eagle is made up of platy gray sandstone and sandy shale.

The Eagle sandstone, which is the equivalent of the Milk River sandstone of southern Alberta, conformably overlies the marine Colorado shale and is overlain conformably by the Two Medicine formation.

No oil or gas is obtained from the Eagle in the Sweetgrass arch area.

COLORADO GROUP

Colorado shale.—This formation covers practically the entire crest of the Sweetgrass arch. Throughout the area it possesses a remarkable uniformity of character and thickness.

The Colorado lends itself readily to division into two distinct lithologic units: the upper or shale member, the lower or Blackleaf sandstone member. The upper member consists of 1,000-1,100 feet of gray and dark gray marine shale, with many iron-bearing, calcareous concretions which occur in beds or zones and many of which weather to bright shades of yellow, orange, and red. Here and there thin sandstone lenses occur in this member.

The Blackleaf member of the Colorado consists of 700-750 feet of alternating beds of gray sandstone, bentonite, and gray and black sandy shale. The sandstone members are lenticular, particularly in the northern part of the Sweetgrass arch. Northwest of Great Falls a group of bentonitic shales, colored delicate shades of pink and green, occur 400 feet above the base of the Colorado. This feature seems to be local, although a few wells drilled in different localities on the arch have recorded colored shales several hundred feet before actually reaching the top of the Kootenai.

The basal sands of the Blackleaf locally contain small amounts of gas in the Kevin-Sunburst field and elsewhere on the arch. The produc-

tive gas sand in the Gladys Belle area north of East Butte, and the productive Bow Island gas sand of southern Alberta occur at the base of the Blackleaf member.

A stray sand near the base of the Colorado in the southeast part of the Kevin-Sunburst field contained small amounts of high-gravity oil. Only two wells were found productive at this horizon and these have not been commercial.

The upper shale member of the Colorado is practically the equivalent of the Benton of southern Alberta, and the Blackleaf member corresponds with the Blairmore formation.

LOWER CRETACEOUS

Kootenai formation.—The Kootenai formation is exposed only in isolated localities in the Sweetgrass Hills and on the southern part of the Sweetgrass arch.

Throughout the area covered by this paper the Kootenai is fairly constant in thickness and general character. South and southwest of the Sweetgrass arch area, however, the Kootenai thickens considerably. At Belt, Stockett, and Sand Coulee the formation contains workable seams of coal. Its thickness ranges from 300 to 500 feet.

The Kootenai, in general, is composed of vari-colored shales, predominantly red, green, or dark gray near the top of the formation, with which are interbedded irregular lenses of sandstone and limestone. The basal part of the Kootenai contains better developed sandstones, the most notable of which is the Sunburst sand. Below the Sunburst sand ordinarily occurs a bed of bright yellow bentonitic shale, which generally marks the base of the formation.

The Sunburst sand is a fine-grained, white quartz sand, ordinarily tightly cemented. Wherever it is sufficiently porous it contains gas, oil, or water. This sand is the source of the gas production in the Kevin-Sunburst gas field. It has yielded gas sufficient to be commercial at the Bears Den, Flat Coulee, Rogers-Imperial area, and Erickson Coulee. On the north end of the Kevin-Sunburst, and at a few localities elsewhere in the field, the Sunburst sand has yielded high-grade oil in commercial amounts.

The Sunburst sand was also the source of noticeable showings of high-grade oil in the Flat Coulee well and in a well drilled in the Pritchard area, northeast of West Butte.

JURASSIC

UPPER JURASSIC

Ellis formation.—The Ellis in the area described in this paper is only partly exposed at a few localities in the Sweetgrass Hills and in the vicinity of Stockett, south of Great Falls. This formation is well known, however, from the logs of wells drilled on the Sweetgrass arch.

The Ellis is a remarkably consistent lithologic unit, both in character and thickness. Its thickness on most of the Sweetgrass arch ranges from 150 to 250 feet, although it is less in the vicinity of Great Falls. West and southwest of Conrad it increases toward the mountains, and a thickness of 300 feet is attained near Pendroy.

The Ellis formation consists of gray to dark gray and brown calcareous shales, with local lenses of medium-grained gray sandstone. In the Kevin-Sunburst field sand lenses occur throughout the Ellis, the more prominent being near the middle and base. Toward the south the basal part of the Ellis becomes predominantly sandy. At the Bannatyne field all except 10 feet of the lower Ellis is composed of a single sandstone member, known as the Emrick or Bannatyne sand.

Northwest of the Bannatyne and southwest of the Kevin-Sunburst, the Ellis thickens and the sand lenses lose their identity. In the vicinity of Conrad and in the Pondera field, the sand members of the Ellis have been replaced by dark gray, calcareous shale.

The extreme base of the Ellis ordinarily contains much pyrite and locally contains light gray clay. In a few places in the Kevin-Sunburst the writer has observed green glauconitic shale near the base of the formation.

The stray sands of the Ellis are locally productive in the Kevin-Sunburst field; the Bannatyne sand is productive of oil at the Bannatyne field.

The Ellis formation unconformably overlies the Madison limestone.

CARBONIFEROUS

LOWER MISSISSIPPIAN

Madison limestone.—This formation has an average thickness of 1,000 feet throughout the Sweetgrass arch area, and its lithologic character is similar wherever it has been penetrated by wells.

The upper 700 feet consists of massive white to cream-colored crystalline limestone, the lower 300 feet is made up of alternating beds of gray and dark gray limestone and shale.

In the Kevin-Sunburst field the upper 150 feet of the Madison is dolomitic and is generally porous enough to carry either oil, gas, or water. The porosity at the Kevin-Sunburst ranges from intercrystalline spaces to fairly large fissures or vugs.

Porosity near the top of the Madison limestone is also prevalent throughout the Sweetgrass arch, but at the extreme top of the formation the amount of porosity is minor except in those localities where oil and gas have been found in commercial amounts.

In the Pondera field the top of the Madison is uniformly porous throughout the producing area, but is only slightly dolomitic.

Between the Madison limestone and the overlying Ellis is a hiatus, representing a time interval which ranges from lower Mississippian to Upper Jurassic. In spite of this profound unconformity the results of wells that have drilled through the Madison in the Sweetgrass arch area indicate that the structure of the Ellis in general is relatively conformable to that of the Madison. Where drilling has been intensive in the Kevin-Sunburst, Pondera, and Bannatyne, a study of the Ellis-Madison contact reveals the probability of local minor topography and minor structure at the top of the Madison.

There is little doubt that the Madison limestone in the Sweetgrass arch area underwent a long period of erosion and peneplanation prior to Ellis deposition, and that such erosion was an important factor in rendering porous the upper part of the formation.

The Madison limestone is the most important reservoir rock in the Sweetgrass arch area. The top of the Madison produces the greater part of the oil in the Kevin-Sunburst field and all the oil in the Pondera field. The top of the lime has also been found productive of gas in the Bears Den area, the Gladys Belle area, the Rogers-Imperial area, the Erickson Coulee area, and the Kevin-Sunburst and Pondera fields.

DEVONIAN

UPPER DEVONIAN

Three Forks formation.—The logs of deep test wells in the Kevin-Sunburst field and on the Sweetgrass arch reveal 320 feet of beds underlying the Madison which are believed to be of Three Forks age. This formation contains three members, from top to bottom as follows: 30 feet of very fine, gray, calcareous sandstone; 70 feet of black, organic shale and gray calcareous pyritic shale; and 220 feet of white to pinkish massive anhydrite containing thin laminae of black calcareous shale.

This lower anhydrite member was designated by Collier[1] as possibly Silurian in age. According to Roy Lebkicher[2] the dark shale and fine-grained sandstone which overlie the anhydrite are typical of the Three Forks formation of the Devonian.

MIDDLE AND LOWER DEVONIAN

Jefferson limestone.—This formation in the Kevin-Sunburst area consists of 540 feet of brown, granular, magnesian limestone, with some white anhydrite.

In four deep test wells drilled in the Kevin-Sunburst, small flows of carbon dioxide gas were found approximately 350 feet below the top of the Jefferson. In one well, The California Petroleum Corporation's Lashbaugh No. 15, SW. 1/4, SE. 1/4, SE. 1/4 Sec. 27, T. 35 N., R. 2 W., a small flow of carbon dioxide gas was found 350 feet below the top of the Jefferson limestone, and immediately under the gas a slight showing of black oil.

The limestones of this formation were tentatively assigned by Collier[3] to the Ordovician, but Lebkicher[4] considers them typically Jefferson.

CAMBRIAN

UPPER AND MIDDLE CAMBRIAN

A deep test well in the Kevin-Sunburst field, drilled by the Potlatch Oil and Gas Company, in 1924, on the Adams lease in the SE. 1/4, NE. 1/4, NW. 1/4, Sec. 21, T. 34 N., R. 1 W., reached a depth of 4,521 feet and penetrated more than 1,400 feet of sedimentary beds below the Jefferson limestone.

The lower 1,400 feet of sediments encountered in the Potlatch well are typical of the Upper and Middle Cambrian of southwestern Montana according to Lebkicher.[5]

These beds fall into three distinct lithologic divisions.

1. Upper member: dense, hard, dark gray to black limestone; thickness, 500 feet.
2. Middle member: gray, green, blue, brown, and red shales with a few beds of argillaceous limestones; thickness, 700 feet.
3. Lower member: hard sandstone and quartzite; thickness, 200 feet.

[1]A. J. Collier, "The Kevin-Sunburst Oil Field, Montana," *U. S. Geol. Survey Press Bull. 4655* (January 12, 1926.)

[2]Personal communication.

[3]*Op. cit.*

[4]Personal communication.

Personal communication.

Considerable variation of opinion has prevailed concerning the last samples taken from the Potlatch deep test. Some geologists have contended that the well was bottomed in a quartz diorite; others considered the samples quartzite.

Drilling has recently been resumed in the Potlatch well, with the result that an additional 5 feet of hole has been made. Samples from this drilling have been observed by the writer, but in his opinion they present nothing conclusive. The samples may be either from the basal quartzite of the Cambrian or from the Belt series (Algonkian). In the writer's opinion the well is not bottomed in an igneous intrusive.

STRUCTURE

REGIONAL STRUCTURE

The area described in this paper was called the Sweetgrass arch by Stebinger.[1] In describing the area he writes,

> the region described is characterized by a very broad anticline or arch that extends in a general northerly direction and is here called the Sweetgrass arch. This broad uplift brings the Colorado shale to the surface in an area about 75 miles wide, surrounded on all sides but the south by outcrops of Virgelle (Eagle) sandstone. The arch extends southward from the Sweetgrass Hills to the region beyond Teton River, where it flattens out because of the presence of gentle northward dips induced by the uplift of the Belt Mountains,....

The preceding description has been adequate when considering the area from a standpoint of surface geology, because outcrops are all too few and unsatisfactory, especially within the Colorado shale area in the region south of Marias River. However, wells drilled throughout the Sweetgrass arch area, during the past seven years, have yielded plenty of subsurface information; consequently, former ideas of the regional structure have been modified.

The accompanying map (Fig. 1) has been prepared from data obtained from the logs of wells drilled on the arch and shows an interpretation of the structure of the top of the Madison limestone at contour intervals of 200 feet.

This interpretation shows the Sweetgrass arch to be more complicated than a simple north-plunging arch. The essential features are two large northwesterly oriented folds situated *en échelon* on a broad uplift which trends slightly west of north from Great Falls to Sweetgrass on the Canadian border. The north fold is known as the Kevin-Sunburst dome and the south fold is generally referred to as the South arch.

[1] *Op. cit.*

On both the Kevin-Sunburst and the South arch are minor cross folds whose orientation ranges from N. 45° E. to N. 60° E.

This cross-folding is less evident at the Kevin-Sunburst than on the South arch, yet it is apparent when viewed on a detailed subsurface map giving the structure at 20- or 50-foot intervals. On the South arch the cross-folding is more evident. The noticeable examples are the Pondera and Bannatyne structures. However, cross-folding is marked at Power and north of Great Falls.

The northeast flank of the Kevin-Sunburst dome is further complicated by igneous intrusions which constitute the Sweetgrass Hills. These intrusions are plugs with related sills and dikes which cut the surrounding Cretaceous strata. The sills are probably the cause of the uplift in the sedimentary beds adjacent to the plugs.

It is interesting to notice that the disturbances caused by the Sweetgrass Hills intrusions have been local and confined almost entirely to a relatively small area between the 0 and 1,000-foot contours on the northeast flank of the Kevin-Sunburst dome (Fig. 1).

East of Great Falls the South arch has been cut by igneous intrusions which form the Highwood Mountains. These intrusions are chiefly plugs and related dikes which seem to have disturbed very little the structure of the surrounding Cretaceous rocks.

According to Clark[1] the folding of the Sweetgrass arch was produced by lateral pressure from the west induced by the Rocky Mountain uplift, offset by the presence of the Highwood and the Bearpaw mountains and the Sweetgrass Hills on the east. He further writes that the folding of the arch was modified by the uplift of the Belt Mountains on the south, which induced northward dips in the arch as far north as Marias River and probably in part induced the folding of Kevin-Sunburst dome.

It is the belief of the writer that the Sweetgrass arch and its subsidiary folds were induced by the combination of the two lateral pressures exerted to the east and northeast, respectively, by the uplifts of the Rocky Mountains on the west and the Belt Mountains on the south, acting along an old line of weakness in the Paleozoic rocks. The old line of weakness or uplift extended approximately north of Great Falls, and is indicated to some degree by the thinning of the combined Kootenai and Ellis along the axis of the arch, with corresponding thickening of the same members on the west and on the east.

A study of the structure in the vicinity of the Sweetgrass Hills and the Highwood Mountains suggests that these uplifts have had little or

[1]Frank R. Clark, "Notes on Kevin-Sunburst Oil Field, Montana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7, No. 3 (May-June, 1923).

no part in the formation of the Sweetgrass arch, and it is probable from present knowledge that both are younger in age than the latter.

Many who have studied the Sweetgrass arch area have regarded the Kevin-Sunburst dome as possibly laccolithic in origin. To date there has been no confirmation of this idea. It is the writer's belief that the dome is the result of compression folding and not due to igneous intrusion.

KEVIN-SUNBURST DOME

The Kevin-Sunburst dome is the most pronounced feature on the north part of the arch. It is a broad, gentle dome, sub-rectangular in outline, with a major axis which trends northwest and southeast. The dome contains approximately 22 townships within its lowest closing contour and has a total closure of 850 feet.

The south end of the Kevin-Sunburst dome extends to Marias River, where it is separated from the South arch by the Marias River syncline, trending east and west.

The oil-producing area of the Kevin-Sunburst dome covers a little more than one township, located northwest of the crest of the dome. The gas-producing area occupies approximately two townships and extends from the crest of the dome southward.

A study of the oil area of the Kevin-Sunburst dome reveals complicated minor structure. Numerous small local "highs" and "lows" are known, all of which have a bearing upon the oil production.

SOUTH ARCH

The South arch is similar to the Kevin-Sunburst dome except that it has an abnormally steep northwest flank and is open at the southeast end. Bounded by the same contour that marks the closure of the Kevin-Sunburst, the South arch covers three times the area of the former. The axis of the South arch trends northwesterly from Great Falls and terminates at a point between Conrad and Pendroy. The northwest flank of the South arch is the steeper and the northeast flank the more gentle.

Pondera structure.—The Pondera structure is a terrace which lies immediately south of the steep northwest flank of the South arch. This terrace is closed on the north, west, and east, but to date drilling has not revealed any structural closure on the south.

Bounded by the 1,800-foot contour, the Pondera structure covers approximately half a township. The proved producing area to date embraces 2,000 acres in the north-central part of T. 27 N., R. 4 W.

Bannatyne structure.—This structure is a small dome with its long axis extending northeast and southwest, and, like Pondera, it has its

steeper flank on the northwest. The lowest closing contour embraces approximately 1,600 acres and the net closure is a little more than 50 feet. The outlined area of production to date is approximately 320 acres.

The Bannatyne structure is productive of oil from the Emrick or Bannatyne sand, a basal sandstone member of the Ellis.

Other structures.—A region of very gentle dips lying higher than the 2,000-foot contour of the South arch and situated southwest of Dutton and west of Power is closed on the northeast, northwest, and southwest. The southeast closure, if any, is slight and is produced by a shallow syncline with northeast trend which is situated just north of Power. This area has been the scene of some prospecting, but only a showing of oil in the Emrick or Bannatyne sand has been found.

Three miles south of Power on Mud Creek a closed structure covering approximately 1,200 acres is now being tested. This structure has 30 feet of closure and is well exposed at the surface in sandstones of the upper part of the Blackleaf (Colorado).

According to Fisher[1] a closed structure is present at Stockett, southeast of Great Falls, with the Madison limestone exposed at the surface. This structure may represent the real "high" of the South arch proper.

SWEETGRASS HILLS AREA

Adjacent to the igneous plugs which make up the Sweetgrass Hills, the sediments have been lifted locally, producing anticlinal noses which radiate from the hills. This same uplifting has produced stresses which in a few places have resulted in closed structures. The better known of the closed structures are the Bears Den and Flat Coulee, which have been productive of gas and showings of oil. Of the noses radiating from the hills, the more important are the Gladys Belle area, the Rogers-Imperial area, and the Erickson Coulee area, all of which are productive of gas. These nose structures, as far as known from meager surface geology and local drilling, are not closed. It is possible that further drilling may ultimately reveal that closure exists, particularly in the Rogers-Imperial and Gladys Belle areas.

SOURCE OF OIL AND FACTORS GOVERNING ACCUMULATION

The oil produced in the Kevin-Sunburst and South arch fields is probably from one of two sources. It has originated in the dark calcareous shales of the Ellis formation and migrated downward into the

[1]C. A. Fisher, "Geology of the Great Falls Coal Field, Montana," *U. S. Geol. Survey Bull. 356* (1909).

Madison limestone, or it has originated in the dark shales and limes of the lower Madison or underlying Devonian and migrated upward into the top of the Madison, the stray Ellis sands, and the Sunburst sand.

The writer believes in the latter source, for the following reasons.

1. It is more logical to assume that the migration of the oil was upward, since the folding is so gentle that lateral migration downward does not seem probable.

2. A core of the Madison limestone from the Troy-Sweetgrass well (NE. 1/4, SW. 1/4, Sec. 21, T. 34 N., R. 1 W.) showed through its entire thickness fractures and cavities filled with oil and oil residuum.

3. The oil found in successively higher sands is progressively higher in gravity than the oil at the top of the Madison, indicating upward migration.

4. Many cores and samples of the top of the Madison limestone contain an oxydized residue of oil probably produced by the weathering of oil which reached the top of the Madison prior to Ellis deposition.

The Madison limestone, at or very near its top, possesses sufficient porosity to permit a comparatively free passage of circulating waters. It is of interest to notice that, in general, where water has been encountered at or near the top of the Madison in wells on the Sweetgrass arch, the water has virtually the same hydrostatic head. This head has been sufficient to cause the water to rise 3,200 feet above sea-level.

The freedom of movement of water below the Ellis-Madison contact has afforded a means of segregation of the oil which has reached the contact from below through joints and fissures. Locally, jointing, fissuring, and minor faulting have been of such importance that oil, gas, and water have had access to further migration upward, and have entered the stray sands of the Ellis, the Sunburst sand, and in places the basal sands of the Colorado.

The upper part of the Madison limestone prior to Ellis deposition was probably rendered porous by weathering processes, principally leaching by ground water along joints and fissures. Following the deposition of the Ellis and younger beds, circulating waters below the Ellis-Madison contact effected replacement, recrystallization, and secondary deposition. The latter processes resulted mainly in an increase in porosity, and the greater increase probably took place in areas that were formerly more porous.

The regional dip throughout the greater part of the Sweetgrass arch ranges from 20 to 50 feet per mile. In localities of minor structure this amount is ordinarily exceeded, particularly on the northwest flanks of

the smaller folds. It is of interest to notice that in the Kevin-Sunburst field, oil at the Ellis-Madison contact is ordinarily found on or adjacent to the steeper flanks of local "highs," and that the flatter or less disturbed areas are barren.

In the Pondera field the oil is found adjacent to the steep northwest flank; in the Bannatyne field the same relation is true for production found in the basal Ellis sand.

The writer believes that the reason for this apparent relationship is two-fold: (1) that in regions of steeper folding greater jointing has occurred in the Madison limestone, thereby providing a better access to circulating waters, which resulted in greater porosity, and (2) that the same jointing and fissuring have given freer channels through which oil could migrate from below.

The amount of structural closure necessary for a fold on the Sweetgrass arch to act as an effective trap for oil is undetermined. In the Kevin-Sunburst field oil is found as low as the 1,600-foot contour on the Madison, although the crest of the dome (2,200-foot contour) is barren. The Kevin-Sunburst dome has 850 feet of closure, yet no oil or gas is found below the 1,600-foot contour. Within the producing area noses that are open toward the crest of the dome are, in many places, productive. Very probably the accumulations are in part due to differential porosity.

The Bannatyne structure, like the Kevin-Sunburst, has sufficient closure to produce oil from the basal Ellis sand, but evidently not enough to be productive from the top of the Madison.

The Pondera field produces only higher than the 1,820-foot contour on the Madison limestone and no structural closure has been found on the south. The oil occurs in the extreme top of the Madison in the producing area. South of the producing area the upper 15-25 feet of the lime is tight and barren.

It seems that the south closure of the Pondera is due wholly to lack of porosity, but it is possible that future drilling will reveal a structural closure, at least on the top of the Madison limestone.

The Kevin-Sunburst field has been rather thoroughly prospected, but on the South arch there are probably minor folds which have not been discovered. It is quite possible that these minor folds may be located by means of test drilling or by geophysical instruments.

It is the writer's opinion that the remaining local "highs" on the South arch are particularly worthy of testing if they are characterized by an abnormal intensity of folding, and especially if they possess a northwest flank steeper than normal.

HELIUM—ITS PROBABLE ORIGIN AND CONCENTRATION IN THE AMARILLO FOLD, TEXAS[1]

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Tulsa, Oklahoma, and Amarillo, Texas

ABSTRACT

The accompanying article is a general discussion of the probable origin of helium. Helium has become one of the important gases and its growing commercial demand brings it to the consideration of the oil and gas producing companies. The writers discuss in particular the occurrence of helium in the Texas Panhandle. They also show the gradual changing of the constituents of the natural gas and its relation to the Amarillo fold.

INTRODUCTION

The presence of helium in the natural gas of the Amarillo fold in the Texas Panhandle gives rise to problems regarding its accumulation and origin, with special emphasis on the relation of the accumulation of helium to geological structure and the possible source. Another subject incidental thereto is the probable influence of the fold on the constituents of the natural gas.

Helium is the most desirable known gas for inflation of aircraft. Although it does not have the lifting power of hydrogen, it is inert, while the latter is highly inflammable. All the known reserves of helium in quantities sufficient for commercial extraction are found in the United States. The national importance of helium supplies makes the subject of its source one of common interest. In the past few years tremendous progress has been made in the design and construction of dirigibles, particularly of the rigid type. The future of transportation by air depends largely upon the development of this type of airship, as it best meets the requirements of safety and ability to carry loads.

Other uses are being found for helium, particularly in decompression for under-water workers, who experience the painful and perhaps

[1]Read before the Association at the Fort Worth meeting, March 22, 1929. Published with permission of Ralph E. Davis and The Prairie Oil and Gas Company.

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[3]Geologist, The Prairie Oil and Gas Company.

fatal "bends" if they emerge too suddenly. The "bends" are believed to be due to an excess of nitrogen gas, which is absorbed by the blood under high pressure and which becomes bubbles when the pressure is relieved quickly. Experiments indicate that an oxygen-helium mixture when supplied instead of air will prevent the "bends," since helium will not dissolve in the blood.

Helium being insoluble in molten metals is used in metallurgy. It is used in filling the interior of nautical and scientific instruments because, although lighter than air, it is stickier, which property dampens the vibration and makes readings easier. Helium conducts heat six times as well as air. Hence it forms an excellent cooling blanket for high-speed dynamos and for the drying of chemicals rapidly.

The gas has other queer characteristics which as yet have not been utilized. Chilled until it changes from a gas to a liquid, helium is the coldest known fluid. It liquefies at about 450° Fahrenheit below zero and in a laboratory experiment has been chilled to the lowest temperature ever produced or within two degrees of absolute zero.

Helium does not combine with other elements, but has in one experiment been suspected of combining with mercury.

OCCURRENCES OF HELIUM

Natural gas from three localities in the United States contains sufficient helium to make extraction for commercial purposes practicable, namely, Petrolia, Texas, central Potter County, Texas, and a locality near Dexter, Kansas. The Potter County, Texas, gas field is the most important. The United States Government has constructed a helium extraction plant at Amarillo, and has set aside for Government use a large block of acreage in the Potter County field.

HISTORY OF FIELD

Inasmuch as the history of the Amarillo gas and oil pools has been ably discussed by several authors,[1] a brief résumé only will be included in this article.

The first gas was discovered in this district in December, 1918, by The Amarillo Oil Company at a location recommended for oil by Charles N. Gould. Other tests were drilled which also produced gas only. In

[1]C. Max Bauer, "Oil and Gas Field of the Texas Panhandle," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 8 (1926), pp. 733-46; "Gas a Big Factor in the Texas Panhandle," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 2 (1928), pp. 165-77.

Charles N. Gould, "The Correlation of the Permian of Kansas, Oklahoma and Northern Texas," *U. S. Geol. Survey Water Supply Paper*, pp. 154-91.

May, 1921, oil was discovered by the Gulf Production Company in what later developed to be the 6666, or Burnett Ranch pool. Since then hundreds of wells have been drilled which serve to outline the present gas-producing area. Further drilling will probably extend the present gas area and several other oil pools as well.

GEOLOGY

The Amarillo fold is a buried granite ridge. This ridge is one of a series of uplifts extending from southeastern Oklahoma northwestward including the Ouachita, Arbuckle, Wichita, and Amarillo uplifts which occurred successively, in the order named, from Mississippian to Permian time. The Amarillo uplift comprises five peaks, the highest of which is the John Wray dome in southern Moore and northern Potter counties. The Carson County peak, known as the 6666 dome, is next in rank, and the White Deer peak, the Wheeler County and Beckham County, Oklahoma, peaks are third, fourth, and last in order.

The top of the "Big lime" series in the highest dome is about 1,600 feet above sea-level. Eastward the elevations of the top of this series are in order: at 6666 ranch, 1,400 feet; at White Deer town, 1,300 feet; in Wheeler-Gray counties, 1,100 feet; and in Beckham County, 800 feet.

About 15 miles south of the John Wray dome in central Potter County is the smaller Bush dome. The top of the "Big lime" is found here only 500 feet above sea-level, with a difference in elevation of more than 1,000 feet within a few miles. A fault having approximately this amount of displacement exists between the two domes. The significance of this fault with reference to the occurrence of helium is important and will be brought out more fully in later paragraphs.

The gas-producing zone of the "Big lime" does not occur on the top of the John Wray dome. The lime comes in contact with the granite and only the non-productive upper part overlies this igneous mass. In places the lime may be entirely absent.

The interval between the top of the Big lime series and the gas-producing zone increases uniformly with distance from the apex of the John Wray dome. However, as the relation has not yet been mapped for the entire fold, discussion will be limited to the region surrounding this dome. In general, the rate of divergence is greatest from the John Wray northeast toward the Anadarko basin and westward toward Channing, and least southward toward the Bush dome and northward near Dumas.

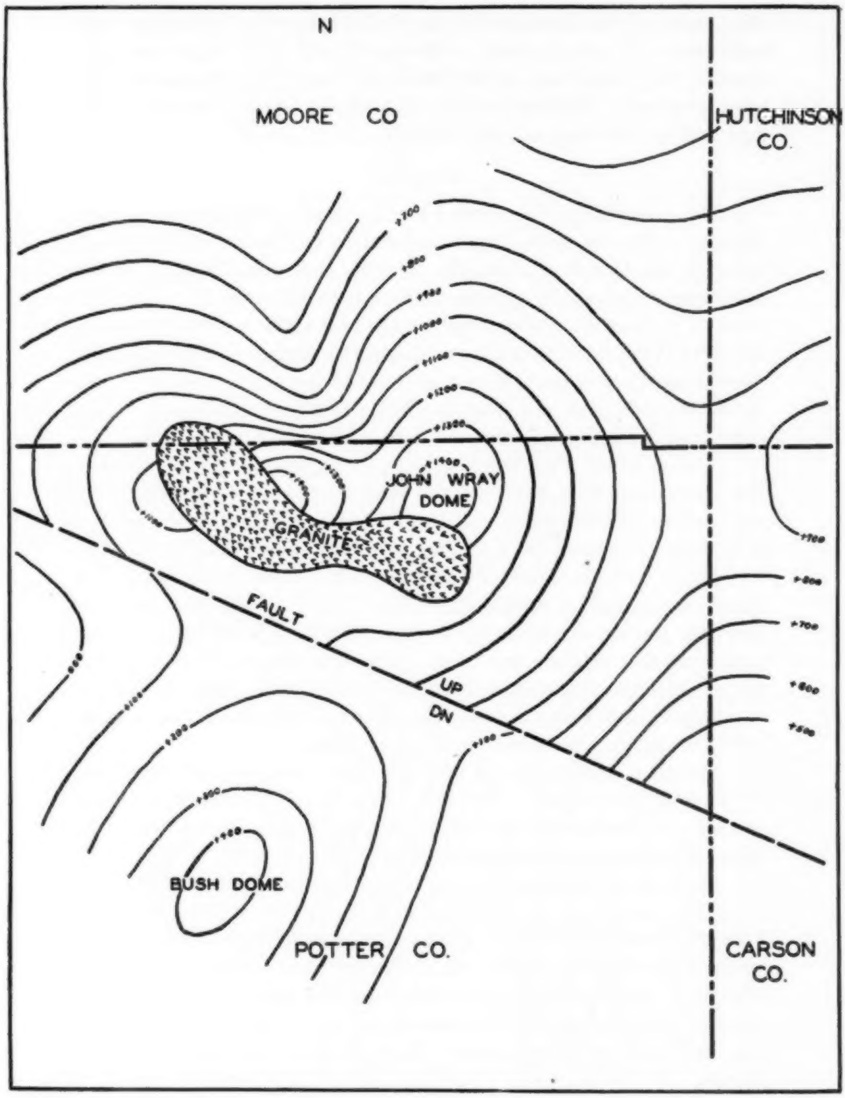

FIG. 1.—Map showing possible contouring on the gas horizon of the "Big lime" series, with outline of the granite-lime contact on John Wray dome. Scale, 1 inch = approximately 11 miles.

The thickness of the "Big lime" differs considerably, as is shown by the few wells which were drilled through the series. From the John Wray dome to the Borger pool the thickness increases from about 100 feet to 900 feet, and it is only about 800 feet thick in northern Moore County in the Morton well. It increases rapidly in thickness toward the south, and in the Bush dome more than 1,300 feet of the series has been logged. Westward to Channing the thickness becomes about 750 feet, and still farther in this direction the lime is gradually transposed to shale.

Whether these facts indicate an unconformable surface at the top of the "Big lime" is uncertain, for, in addition to the change in the position of the pay streaks with respect to the top, there appears to be a decided change in interval from the gas zone to the bottom of the lime series. This is especially noticeable toward the south, where the thickest lime is recorded, but the gas zone remains near the top. Erosion on the upper surface of the lime, particularly on the structural "highs," probably has taken place, and tends to accentuate the thickening toward the synclines.

All reference to structure will be to that as mapped on the "Big lime" series with the knowledge that variations occur as previously mentioned.

OCCURRENCE OF NATURAL GAS

Natural gas is found throughout the Amarillo fold, principally in the "Big lime" series, but a small amount occurs in the "Cavey red shale" series above. The producing area conforms to geological structure. The gas is found in the higher parts of the fold, and is surrounded by water, and the oil occurs on the flanks of the fold directly above the water level. No particular reason can be assigned for the concentration of the oil in isolated pools instead of in continuous belts, unless this is due to porosity. Oil has also accumulated in the granite wash below the lime.

Although the gas zone of the "Big lime" is absent over much of the top of the John Wray dome, gas is found in sand lenses of the "Cavey red shale" series. The similarity of the gas analyses and the uniformity of rock pressure suggest the migration of gas from the lime series to the "Red shale" series through faults, fissures, or along an unconformity. No gas has as yet been found in the lime, in which commercial production was first encountered in the "Red shale" sands. This may be accidental, for the gas area is controlled by the size of the sand lenses, the deposition of which in turn may have been controlled by the shape of either the granite ridge or the top of the lime surface.

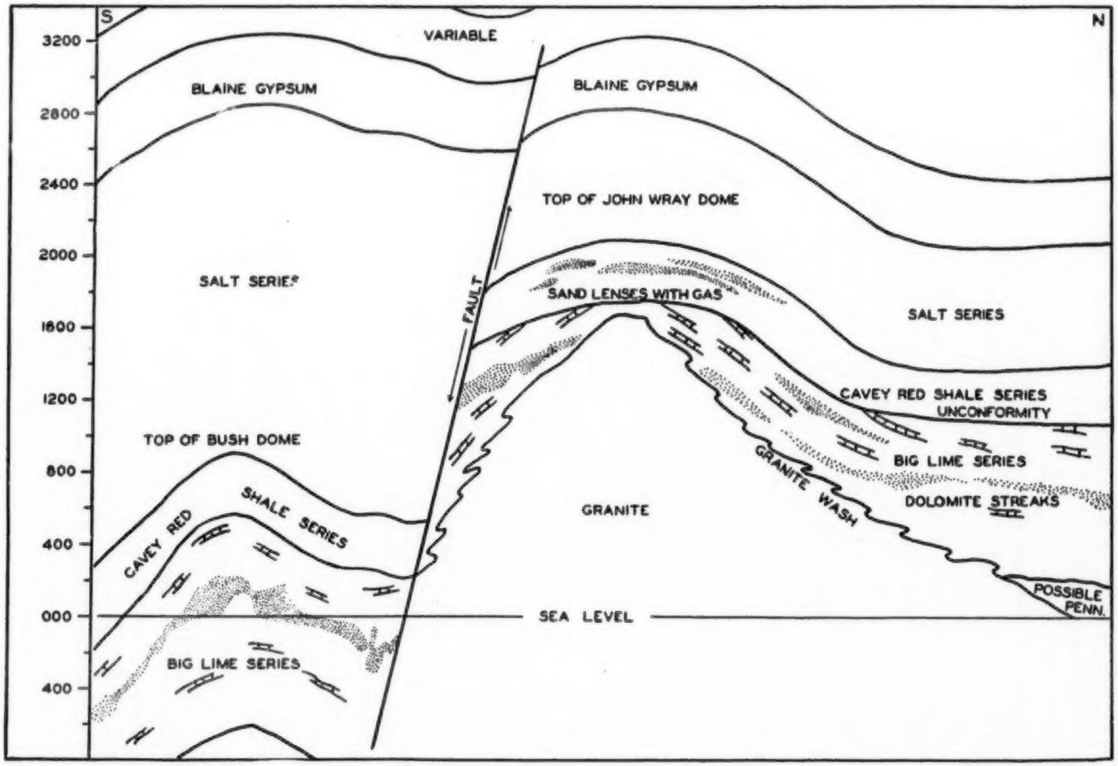

FIG. 2.—Diagrammatic section from Bush dome north across fault to Dumas in Moore County. Depths shown in feet. Section generalized, not to scale.

GAS PRESSURE

The virgin gas pressure in the main field was 430 pounds, whether in Moore County or more than 100 miles east in Wheeler County. Water rises 1,000 feet in the wells at the edge of the field, suggesting a hydrostatic head equivalent to a pressure of 430 pounds. It is believed by some geologists that the hydrostatic head has its origin in the Wichita Mountains of Oklahoma, where the granite-sedimentary contact is found at approximately 1,000 feet above sea-level.[1] The gas pressure of the Bush dome is 720 pounds. A downthrow of 1,000 feet by faulting is sufficient to have increased the rock pressure from 430 to 720 pounds. It is also possible that the pressure of the gas in the entire Panhandle area approximated 720 pounds until the strata were exposed by erosion in the Wichita Mountains. Gas in the Bush dome, separated from the John Wray dome by faulting, remained at higher pressure, while on the main fold the pressure declined. The gas zone under the Bush dome is at nearly the same elevation above sea-level as many gas wells found on the flanks of the main fold; consequently, the increase of pressure is not due to the position of the zone with respect to sea-level. There are objections to either assumption on the basis of present knowledge of the geological structure.

HELIUM IN AMARILLO FOLD

Helium is found primarily in the Bush dome. The proved gas reserves of this dome are large, and, as the helium content is 2 per cent, a supply of this gas is assured for many years. The nitrogen content is approximately 25 per cent. An affinity between helium and nitrogen has been thought to exist, as their association and occurrence has been noticed in several fields. Many gases with an exceptionally high nitrogen content showed upon analysis no helium, but few containing helium contained no nitrogen.

It has been suggested that any air trapped in the beds at the time of deposition might have been reduced principally to nitrogen by the withdrawal of oxygen for oxidation of minerals included in the formations.[2] The migration of the natural gas, although gradual, might have propelled the nitrogen and helium to the higher parts of the fold. If this occurred, then the Bush dome might have been the highest of the series of folds during the long period of accumulation and concentration of gases.

[1]Suggested by Robert H. Wood, personal communication.

[2]A. J. L. Hutchinson, chemical engineer, personal discussion.

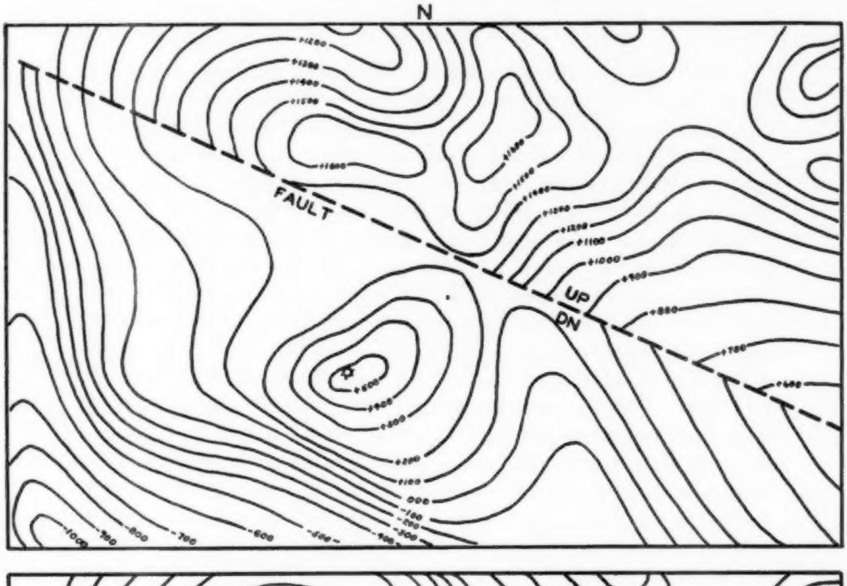

FIG. 3.—Map showing contours of lime top on John Wray dome, northern Potter County, Texas. Upper—after faulting. Lower—before the main period of faulting and at time of helium accumulation. Scale, 1 inch = approximately 6½ miles.

The Bush dome was at one time presumably a part of the John Wray dome. The thick salt series south of the fault suggests that the displacement and separation occurred during the deposition of the salt. If it did so occur, then the natural gas had sufficient time to fill the original dome. The faulting produced the smaller Bush dome, and the gas left on the south side of the fault concentrated thereunder in its original pressure or a changed pressure.

It was concluded, in view of the probable origin of the Bush dome, that helium might be present in the gas surrounding the John Wray dome. Tests were then made and it was found to be present, but in smaller amounts.

Gas encountered in the "Red shale" sands on the John Wray dome has a much lower average nitrogen content than that of the gas in the "Big lime" near it, although the source of both gases was evidently the same.

SOURCE OF HELIUM

Helium is known to be derived from radioactive minerals, particularly uranium, and some helium is even ascribed to thorium or its radioactive descendents. Uranium is constantly breaking down into an element of less atomic weight. The derived element changes to one of yet lower atomic weight. The alpha ray of the uranium-radium transformation has been recognized as helium. The rate of elevation was measured and found to be 316 cubic millimeters per year in a hypothetical mineral containing one gram of radium.

Emanations of helium have been noticed in thermal springs in various parts of the world, in the soils of the earth, and as a general constituent of natural gas.

The researches of several European scientists show that supplies of helium can be traced to the radioactivity of rare and common minerals, in rocks both igneous and sedimentary.[1]

Uraninite is the principal source of uranium and its compounds. A fact of particular importance in connection with the problem of helium in relatively large quantities in the Amarillo field is the occurrence of uraninite as a primary constituent of the pegmatites in the Llano-Burnet region of Texas. Paige[2] reports yttrialite, fergusonite, mivenite,

[1]J. Joley, *Radio Activity and Geology*, Archibald Constable and Company (London, 1908).

[2]Sidney Paige, "Mineral Resources of the Llano-Burnet Region, Texas," *U. S. Geol. Survey Bull. 450* (1911).

lanthanite, and other rare minerals commonly associated with uraninite, which are alteration products or admixtures thereof.

It is highly possible that the reservoir rocks in the Amarillo area are in contact with pegmatites and granites containing radioactive minerals. The constituent radioactive minerals of the sedimentary rocks, where important quantities were included, can likewise account for the occurrence.[1] This is probably the explanation of the Fort Worth and Kansas accumulations, where no igneous rocks in the immediate region are as yet known to be in contact with the reservoir.

The Bush dome probably obtained its helium content from the main source before the major faulting occurred and its consequent separation from the John Wray dome. In the opinion of Bauer[2] the diminishing amount of helium in the main structure eastward indicates a source for the helium on or near the John Wray dome. He also agrees with the general belief that the hydrocarbon gases and oil came largely from the Anadarko basin on the north, moving up along the unconformity between the Permo-Carboniferous sediments and the granite, into the porous strata of the higher parts of the structure. Dissipation of the helium north of the Potter County fault may have taken place when the Wichita Mountains were eroded to a sufficient depth to expose the granite-sedimentary contact, thereby relieving the pressure and causing a great expansion in the gas of the John Wray, 6666, and other domes on the main structure; whereas the gas in the Bush dome remained concentrated.

CONSTITUENTS OF NATURAL GAS WITH REFERENCE TO GEOLOGICAL STRUCTURE

The change in the percentage of constituents of gas from the top of the John Wray dome eastward along the granite ridge to Wheeler County is interesting, although no definite explanation can be given for the difference. As previously stated, there is an east dip on the axis of the granite ridge of more than 500 feet within a distance of about 75 miles. All following references to structure will be to the elevation of the top of the "Big lime" above sea-level. As shown earlier, the relation between the gas zone and the top of the "Big lime" is not uniform, but will suffice for the purpose of this discussion. The average analyses to follow were derived from many analyses throughout the field.

[1]G. Shelburne Rodgers, "Helium-Bearing Natural Gas," *U. S. Geol. Survey Prof. Paper 121* (1921).

[2]C. Max Bauer, personal discussion.

The nitrogen (specific gravity, 0.967) content of the gas decreases gradually from more than 12 per cent at the 1,500-foot contour in Moore and Potter counties to 2 per cent at the 800-foot contour in north-central Wheeler County. In this same distance (1) the methane (specific gravity, 0.554) content increases gradually from 65 per cent to about 83 per cent; (2) the ethane (specific gravity, 1.038) content decreases gradually from 24 per cent to 12 per cent; and (3) the total density (specific gravity) of the gas decreases gradually from approximately 0.72 to 0.62.

The phenomena can not be attributed to the process of gravitation as this view is held by some authorities to be untenable. Again, the law governing the rate of diffusion of gases does not seem to apply if the source of oil and gas is assumed to be in the Anadarko basin. In fact, so many factors tend to involve the situation that it is doubtful whether any satisfactory explanation can be advanced. The size of the capillary openings, the rate of formation of the gases, the period of time since the generation of the gases and concentration in the fold, which, except for other limiting conditions, should have been sufficient for a re-diffusion of the gases, the formation of the fold, the pressure changes, and many other factors must be considered. The process is a heterogeneous reaction with many unknown premises covering the chemical, physical, and geological processes.

CONCLUSIONS

Helium and possibly nitrogen are derived from a different source from the natural gases in which they are found. Helium evolves from inorganic sources, namely, radioactive minerals, whereas the nitrogen so commonly associated with it is probably derived from the air entrapped in the sedimentary beds during deposition. The helium may concentrate in the higher parts of the fold because of its specific gravity, but probably is assisted in the process by the migration and infiltration of natural gas into the reservoir. The gravitational separation of a gas is held by most authorities to be impossible, but, in view of the tremendous period of time involved, may be probable.

The explanation of the gradual changing of the constituents of the natural gas across the fold may never be fully learned. With the large range of chemical, physical, and geological processes affecting the conclusions, many of which can not conceivably be discovered, an unimpeachable explanation is improbable.

It may be added that because of the rare combination of conditions making a commercial concentration of helium possible, every effort

should be extended to conserve the supply. The quantity available in the largest reserve yet known, the Bush dome, when transformed into airship requirements, is only sufficient for a few thousand of the type of the Graf Zeppelin. This will be insignificant when transportation by air assumes major importance.

OIL AND WATER CONTENT OF OIL SANDS, GROZNY, RUSSIA[1]

NORBERT T. LINDTROP[2] and V. M. NIKOLAEFF[3]
Grosny, U. S. Soviet Republics

ABSTRACT

The writers conclude from their laboratory study of the displacement of oil by water, in sands of different size of grain, that it is very important to consider the relatively large amount of water retained in the reservoir sand after ordinary production of the wells ceases. It may be that more oil is produced by present methods than is generally estimated, and that estimations of unrecovered oil are too large if water is retained in the pore space of the sand in such important quantities.

The recovery from the Grozny district flowing sands is 12½ per cent of the sand (strata) volume. After the encroachment of water, this depleted sand does not give any commercial production. The laboratory tests show that 72.5 per cent of the oil is obtainable from the Grozny oil-saturated sand, by flooding. But a considerable quantity of Grozny connate saturated water remains, when the water sand is saturated with oil, that is, at restored natural conditions. Actual production in the field, by flooding, yields 54 per cent of the oil from such a sand, that is, less than in the oil-sand tests.

The data presented are only preliminary, but if the tests prove that a considerable quantity of connate water is present in the sands, then it is necessary to conclude that our pools contain less unrecovered oil than previously estimated.

Many scientific investigations have been made regarding underground conditions in oil-bearing strata. The fundamental purpose of these investigations is to determine the quantity of oil that is obtainable by modern methods of production.

Most of the investigators completed their tests with dry sands exclusively, saturated with different oils. As will be seen, the dry sand tests may lead to incorrect conclusions, whereas the correct determination of the quantity of oil underground provides the information for deciding the rate at which it may be depleted and for applying the proper producing methods in different pools.

The determination of the quantity of oil available from sands in the Grozny district by means of flowing wells is very important because flowing wells provide about 64 per cent of the total production.

[1]Manuscript received by the editor, March, 1929.

[2]Chief geologist, Grosneft Government Trust.

[3]Chemist, Grosneft Government Trust.

Flowing wells are obtained in "Solenaya Balka" of the Old Grozny field from sandstones XI and XII, and in the New Grozny field from sandstones XIII, XVI, and XXI.

The flowing production in the Grozny field is due to the hydraulic control; and the depletion begins with encroachment of high-pressure edge water. Most of the oil is produced from flowing wells, and a very small quantity is available by pumping after the encroachment of edge water.

Calculations for depletion of some parts of the field show that from the sandstones whose average thickness is 175 feet, the volume of oil obtained is 12½ per cent of the volume of the strata, that is, the volume of oil obtained is equal to about 50 per cent of pore space, if it is assumed that the average porosity of pay sands is 25 per cent. Such a recovery of oil is relatively large; nevertheless, we have to determine what fills the remaining pore space.

Keeping in mind the hydraulic control in the Grozny fields, an insignificant gas-oil ratio, namely, 95-140 cubic feet per barrel of oil, and the high hydrostatic water level after depletion, we must exclude the possibility of any quantity of undissolved gas in the oil sands. It is necessary, therefore, to deduce regarding the unused half of pore space (if it is not really less than assumed) that it is filled with a liquid, namely, partly with oil and partly with water. There are many evidences that some quantity of oil remains by adhesion in the pores of strata after depletion. It is known also that this quantity depends on the size of sand grain and the quality of oil.

Table I shows the results of laboratory tests of displacing oil products in water sands of different grain size.

These figures show that oil sand, if the oil is displaced by water, loses 75 per cent of its total oil. High temperature increases slightly the quantity of recoverable oil. These tests do not take into account the natural conditions of formation of oil beds, and dry sands were saturated with oil.

Analyzing every pool, one can readily imagine the following sequence of its formation. During the first period, the sands or other porous rocks (mostly calcareous) were partly cemented with some mineral deposited from solution. In the period of orogenesis the anticlines were formed. Partly in this stage, but mostly after it, the oil came into the porous formation, displacing the water from the upper part of the folds to the lower. It is natural to assume that, while this displacement took place, some of the water remained in the pore spaces. The amount of

TABLE I

Number	Size of Opening		Theoretical Porosity (Per Cent)	Filling Liquid Porosity (Per Cent)	Displacing Oil by Water (Per Cent of Sand Volume)		Recovery of Hydrocarbons from Sand (Per Cent of Total Pore Space)	Remarks
	Through	Caught on			Oil Displaced	Oil Remaining		
1	8 mm.	3 mm.	35.5	35.5	25.5	10.0	71.8	Oil (gravity 0.851) and fresh water at 28° C.
2	..	..	36.2	35.9	26.3	9.6	73.2	
3	40	60	39.5	38.4	29.7	8.7	77.3	The same oil and water at 70° C.
4	20	..	46.1	45.8	38.4	7.4	83.8	
5	20	..	43.0	36.2	28.8	7.4	79.5	Kerosene (gravity 0.764) and fresh water at 21.5° C.
6	20	..	40.2	34.8	25.9	8.9	74.4	

water remaining in pores depended evidently on the size of the pores, the displacing force (pressure), and other causes. Under some conditions of hydraulic pressure, more water remains in subcapillary pores than in large pores. Some water remains at the points of contact of the sand grains.

To clear up the conditions in the New Grozny oil field, a series of preliminary experiments with collaboration by A. Malyshev were completed. The sands tested were from the Tertiary oil-bearing formations. Samples were taken from outcrops on the river Argun 35 kilometers from Grozny. These sands at the outcrop are not cemented and consist almost entirely of pure quartz.

Table II illustrates the size of sand grain. The sand was sifted through five different standard sieves.

TABLE II

Grain Size		*The Sands of Oil-Bearing Formation*						
Through	*Caught on*	1	2	13	13	15	17	19
20	40	1.5	1.0	0.5	4.6	0.9	3.8	9.0
40	60	1.5	45.2	1.5	4.0	1.2	3.8	30.7
60	80	8.8	39.0	8.5	6.0	8.9	6.4	28.1
80	100	18.8	4.0	14.0	22.8	9.0	7.6	18.0
100	..	69.4	10.8	75.5	62.6	80.0	78.4	14.2
		100.0	100.0	100.0	100.0	100.0	100.0	100.0

Most of the Grozny sands are fine-grained, but some strata are largely coarse-grained. For most of the experiments coarse sands were used, that is, sands which went through 40-mesh and caught on 60-mesh.

The test regarding ultimate recovery of oil from sands was conducted in the following order. Glass tubes ⅞ inch to 1½ inches in diameter and 24-27 inches long were filled with sand, the sand level being 5 inches lower than the top of the tube. The theoretical sand porosity was determined from its specific gravity and volume weight, and it ranged from 35.3 to 47.6 per cent for these tests. The sand in the tubes was filled with water from the lower end of each tube. The water porosity was determined after weighing; this porosity is less than the theoretical porosity, because some of the pore spaces were filled with air.

After the sand was saturated with water, it was flooded with the oil from the upper end of the tube, until clean oil was received from the

outlet tube in the cylinders, located at the bottom of each tube. The displacing of water by oil left some water in the pores. Oil saturation of the sand in the tubes was completed during different time periods ranging from several minutes to several hours.

The average total volume of pores filled with the water and oil for all tests is 37.7 per cent, as compared with the theoretical porosity of 39.0 per cent. The difference is 1.3 per cent of the volume, or 3.3 per cent of the pore space. Porosity, as determined by water and oil, is used in comparing the data on ultimate recovery of oil from the sands.

After the sand was saturated with oil, it was washed with water from the bottom to the top. It was possible then to state that the percentage of ultimate oil recovery from the sand, saturated with water before and washed with oil after, is less than that of dry sand, saturated immediately with oil. In the experiment the static pressure ranged from 12 to 58 inches.

In the first series of experiments, tubes with sand were saturated with fresh water. After the water was displaced by oil of 0.855 gravity and 1.73 Engler viscosity at 20° C., the oil was in turn displaced with the same water.

These experiments show that the gravel and coarse sands are saturated better with oil than fine-grained or mixed sands. The ultimate recovery of oil in gravel, from total volume of oil, is 90 per cent, and the same for medium-sized sands is 61.5-68.2 per cent. The remaining oil ranges from 31.8 to 38.5 per cent.

From this experiment, disregarding the gravel tests, it may be seen that, under laboratory conditions of flooding oil sands with fresh water, the recovery is 54.4 per cent of pore volume, 29 per cent of oil remains in the sand, and 16.6 per cent is filled with connate water. As the tests were completed within a relatively short time, it is possible that with longer periods of time the quantity of connate water would decrease and that of oil recovered would increase.

Besides tests in Table III, similar experiments were completed with sands by application of oil-field water and other solutions, such as distilled water; oil-well water containing salts, mainly NaCl, amounting to 26 gr. per liter; oil-well slightly mineral water; alkaline water, containing salts amounting to 0.8-1.0 gr. per liter; and sodium solution, containing 4.5 gr. Na_2CO_3 per liter.

From the data of Tables III and IV it is possible to make the following summary.

TABLE III

Number	Grain Size		Theoretical Porosity	1st Stage: Flooding Water Sand by Oil (Per Cent of Sand Volume)			2nd Stage: Flooding Oil by Water (Per Cent of Sand Volume)		Quantity of Recovered Oil (Per Cent of Total Oil Volume)	Quantity of Recovered Oil (Per Cent of Total Pore Space	Flooding Time, Minutes	
	Through	Caught on		Quantity of Oil in Sand	Quantity of Remaining Water	Total Pore Space Volume	Quantity of Oil Displaced	Quantity of Remaining Oil			Water by Oil	Oil by Water
1 }	8 mm.	3 mm.	35.3	31.2	4.5	35.7	28.2	3.0	90.4	79.0	3.4	2.4
2 }	8 mm.	3 mm.	36.2	29.5	5.9	35.4	26.2	3.3	88.9	74.0	9.2	1.5
3 }	8 mm.	3 mm.	36.1	31.2	5.0	36.2	25.0	6.2	80.1	69.0	11.3	1.0
4	40	60	38.4	33.5	5.1	38.6	20.6	12.9	61.5	53.4	22.0	10.0
5	40	60	38.4	30.2	5.4	35.6	20.6	9.6	68.2	57.8	2.3	1.1
6	40	60	38.0	32.2	5.1	37.3	20.4	11.8	63.4	54.7	2.7	1.8
7	20	..	36.5	25.8	8.7	34.5	17.1	8.7	66.3	49.6	39.7	19.0
8	20	..	38.0	30.8	6.2	37.0	20.7	10.1	67.2	56.0	3.9	3.3
9	20	..	38.0	30.9	5.9	36.8	19.9	11.0	64.4	54.0	4.0	3.5

1. In all the experiments (except 10, 17, and 18, where oil saturation was made partly unequally and partly incompletely) 6.8 per cent of sand volume or 18.2 per cent of pore spaces is filled by connate water. This result shows that relatively large pore volume can not be filled with oil during saturation of water sand by oil.

2. The recovery of oil from sand, saturated with salt water, is essentially less than that from sand saturated with alkaline or slightly mineralized waters.

3. In displacing oil from sand by concentrated salt water, the recovered quantity of oil is less than a half of its total volume.

4. The ultimate oil recovery increases when slightly mineral water is used.

5. In fine-grained sand a larger quantity of oil remains than in coarse-grained sand.

6. The highest ultimate oil recovery is obtained when sodium solution is used.

Comparing data of ultimate oil recovery from dry saturated sands (Table I), where it is 72.5 per cent, with the data of saturated water sands where the conditions were more natural (Tables III and IV), it was found that in the second case the average ultimate oil recovery is 54.8 per cent, that is, essentially less than in the first case. The difference between recovery of oil is 17.7 per cent, or the same amount which is left in the sands as connate water. These facts require more detailed investigations, and it is necessary to keep this in mind in calculation of the total oil underground.

The laboratory data regarding water in oil sands agree in general with practical data. Production from flowing wells in the Grozny fields shows that approximately 0.25-0.5 per cent of water is obtained with the oil. This water is connate in the oil sands and has no relation to the edge water.

Experiments on oil sand from the "Shubaninskaya" gallery in the Baku district which was completed 1921-23 also show the existence of water in oil sands. Samples were taken from the gallery walls in September, 1928. The oil and water content of these samples is shown in Table V.

These data show that almost no gas was in the sand, as all pore space was filled with water or oil. The average quantity of water in this sand equals 3.7 per cent of the sand volume, or 12.1 per cent of pore volume.

Comparing these data with those of laboratory experiments in which the average water content is 6.8 per cent of sand volume, or 18.2 per cent

TABLE IV

Number	Grain Size		Theoretical Porosity	1st Stage: Flooding Water Sand by Oil (Per Cent of Sand Volume)			2nd Stage: Flooding Oil by Water (Per Cent of Sand Volume)		Quantity of Recovered Oil (Per Cent of Total Oil Volume)	Quantity of Recovered Oil (Per Cent of Total Pore Space	Flooding Time, Minutes	
	Through	Caught on		Quantity of Oil in Sand	Quantity of Remaining Water	Total Pore Space Volume	Quantity of Oil Displaced	Quantity of Remaining Oil			Oil by Water	Water by Oil
Salt Water from Well—Oil—Salt Water from Well												
10	40	60	37.2	21.5	16.4	37.9	8.6	12.9	40.2	22.7	17	23 hours
11		..	36.8	22.4	10.9	33.3	9.5	12.9	42.6	28.5	234	86
12	20	..	36.8	28.8	6.6	35.4	13.7	15.1	48.0	38.7	39	34
13		..	38.0	26.4	10.1	36.5	11.8	14.6	44.5	32.4	240	75
Water from Sand XIII—Oil— Water from Sand XIII												
14	3 mm.	8 mm.	37.6	30.5	6.7	37.2	25.9	4.6	84.9	69.5	....	2.5
15	40	60	40.9	32.7	7.6	40.3	21.8	10.9	66.8	54.0	1.2	23.0
16	60	80	41.5	33.2	8.0	41.2	20.8	12.4	63.0	50.5	1.4	1.0
17	80	100	41.0	22.0	14.9	36.9	6.9	15.1	31.3	18.7	10.0	24 hours
18	100	..	47.6	20.7	26.0	47.6	7.9	12.8	38.1	16.6	12.0	24 hours
Distilled Water—Oil—Distilled Water												
19	60	80	39.4	32.2	7.1	39.3	19.7	12.5	63.2	50.1	...	...
20	60	80	40.0	33.1	6.9	40.0	19.9	13.2	60.0	49.7	12	83
21	60	80	36.9	28.6	9.5	38.1	16.1	12.5	56.4	42.2	25 hours	60
22	60	80	40.3	33.4	6.6	40.0	21.5	11.9	64.3	53.7	10	45 hours
23	60	80	37.9	30.7	6.9	37.6	19.2	11.5	62.4	52.0	...	...
24	60	80	42.0	28.8	9.6	38.4	16.3	12.5	56.5	42.4	15 hours	....
Sodium Solution—Oil—Sodium Solution												
25	40	60	38.0	31.7	5.4	37.1	23.4	8.3	73.7	63.0	73	...
26	60	80	38.2	34.3	3.1	37.4	27.3	7.0	79.5	73.0	200	...
27	80	100	43.5	30.0	6.6	36.6	19.1	10.9	63.8	52.2	2	65
28	80	100	43.5	32.1	7.0	39.1	28.3	3.8	88.0	72.3	262	104

TABLE V

Number	*Distance from Gallery Mouth, Feet*	*Water Content (Per Cent of Sand Volume)*	*Oil Content (Per Cent of Sand Volume)*	*Total Oil and Water (Per Cent of Sand Volume)*	*Clean Sandstone Porosity*	*Per Cent of Water Content*
1	749	3.5	27.7	31.2	32.9	10.6
2	840	3.0	[illegible]	26.3	28.4	10.6
3	840	3.8	23.3	27.1	28.5	13.3
4	875	4.4	27.0	31.4	31.9	13.8

of pore volume, it is clear that in samples from the gallery there is less water than in the laboratory samples. The small amount of water in samples from the Shubaninskaya gallery might be explained by weathering, because this gallery was completed a long time ago. These laboratory tests and investigations of samples from the Shubaninskaya gallery show the presence of some connate water in oil sands.

Studies of sandstone samples (cores) taken from drilling wells support these laboratory tests. An interesting example of such records is the investigation of Fettke,[1] who tested the content of core samples from the well No. 4 of the Brunded Oil Corporation and F. Tracy No. 22, Oil City district, Pennsylvania.

The sands in the Oil City district are generally fine-grained, and detailed investigation of cores from two wells (No. 4 and No. 19), where the thickness of the formation was 20.85 feet and 53.61 feet, respectively, showed the size of grain as given in Table VI.

The writer investigated the content of pore space in the oil sand in 9 samples from well No. 4 and in 8 samples from well No. 22. The results are given in Table VII.

Considering the figure of water content in percentage of sand volume, we see that the average figures for all investigations of both wells are 7.0 and 5.8 per cent, respectively. It is possible, as Fettke states, that part of the water was from outside.

Different causes explain such a retention of water in sand, the most important of which is the presence of subcapillary pore space, especially in fine-grained sands. A considerable quantity of water remains also at the points of contact of the sand grains.

[1]Charles R. Fettke, "Core Studies of the Second Sand of the Venango Group from Oil City, Pennsylvania," *Amer. Inst. Min. Met. Eng. Petroleum Development and Technology, 1927*; "A Year's Application of Air at Hamilton Corners," *Oil Weekly* (March 9, 1928).

TABLE VI

Grain Size		*Well No. 4*	*Well No. 19*
Through	*Caught on*	*Per Cent*	
..	35	16.2	5.7
35	48	8.1	10.1
48	65	7.8	11.3
65	100	21.2	38.3
100	150	27.1	22.2
150	...	19.6	11.4
		100.0	99.0

We observe almost complete identity in the study of cores (well No. 4 and well No. 22) and sand tests in laboratory conditions; therefore, we are justified in making the most probable deduction, that the phenomena described take place in nature in the formation of oil fields.

Disregarding possible defects in the experiments and the preliminary character of tests, we must nevertheless conclude that there is always some connate water in the oil sands. This problem is important and requires detailed and accurate analysis.

CONCLUSION

Returning to the consideration of ultimate oil recovery from sands through flowing wells in the Grozny district, where the average strata porosity was 25 per cent, we can accept the following distribution of pore space between water and oil in sand: 12.5 per cent of the sand volume is represented by oil obtained during the producing period, after which this volume is occupied by water; 5-7 per cent of the volume is connate water, which remained during the saturation of the sands by oil; the remaining part of the volume, 5.5-7.5 per cent, is filled partly with oil (through surface tension). Some of this oil may be liberated under favorable conditions and collected toward the top of the fold and might be produced afterward from the sand.

It is fairly possible that the average porosity of the strata is even less than 25 per cent; if so, we must suggest that the quantity of produced oil and connate water is invariable, and that the amount of oil held back by surface tension in the Grozny fields, where the sands are flooded with hot water, is even less than 5.5-7.5 per cent. Thus, as part of the pore space in oil strata is filled with water, the recovery from the oil pool is

TABLE VII

Well No. 4						Well No. 22					
Numbers of Samples	Total Pore Space by Volume (Per Cent)	Content (Per Cent Pore Volume)			Water Content (Per Cent Sand Volume)	Numbers of Samples	Total Pore Space by Volume (Per Cent)	Content (Per Cent Pore Volume)			Water Content (Per Cent Sand Volume)
		Oil	Air or Gas	Water				Oil	Air or Gas	Water	
1	21.6	26	27	47	10.2	1	12.2	16	69	15	1.8
2	22.5	27	44	29	6.5	2	13.3	14	59	27	3.9
3	20.5	40	22	38	7.8	3	8.4	34	11	55	4.6
4	21.9	29	45	26	5.7	4	17.6	26	29	45	7.9
5	19.2	28	41	31	6.0	5	16.2	22	35	43	7.0
6	17.1	24	49	27	4.6	6	16.2	22	35	45	7.3
7	9.6	31	26	43	4.1	7	19.3	21	39	40	7.7
8	23.1	16	43	41	9.5	8	15.3	23	35	42	6.4
9	18.4	26	26	48	8.8	...	..	..	..	..	..
Avg.	19.3	27	36	37	7.0	Avg.	14.8	22	39	39	5.8

very high, particularly because of hydraulic control and absence of gas in the oil sands.

We wish to emphasize the importance of the relatively large amount of connate water retained in the sand; not enough attention has been given this condition. It is necessary, therefore, to make a detailed study of physico-chemical relation of oil, water, and sand in the strata. This relation has been studied in detail by P. G. Nutting.[1]

The question of connate or retained water in strata can not be considered as solved completely by these data, which must be considered only as a preliminary experiment for clearing up our understanding of underground conditions.

If the fundamental deduction about the content of connate water in strata together with oil is later proved, then the recovery of oil is greater than previously was supposed, and some of the existing calculations regarding additional oil recovery must be lowered.

[1]P. G. Nutting, "Some Geological Consequences of Selective Adsorption."

MICROTHERMAL STUDIES OF SOME "MOTHER ROCKS" OF PETROLEUM FROM ALASKA[1]

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DESCRIPTION OF THE FOSSIL PLANTS

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ABSTRACT

This paper contains preliminary results of studies of supposed "mother rocks" of petroleum from northern Alaska by means of a microfurnace, with the object of determining (1) the relative values of the various visible components of the rocks as sources of oils, and (2) the qualities of the oil yielded by each and the temperatures at which the yield takes place. It describes the physical and optical properties of each rock, and records the observed changes of state in the different visible components as the temperature rises under close control and with measurement to ⅕° of accuracy in an inert atmosphere at normal pressures. These records of critical temperatures are in effect constants newly established in this work.

General results are discussed at the end of the account of the microthermal studies.

INTRODUCTION

The examinations reported in this paper were based on specimens representing four different types of supposed "mother rocks" of petroleum collected by Philip S. Smith, of the U. S. Geological Survey. They were gathered in 1925 and 1926, in the course of the exploration of the stratigraphy and structure of parts of the Arctic slope of northern

[1]Project No. 3 in the research program of the American Petroleum Institute. Financial assistance in this work has been received from a research fund of the American Petroleum Institute donated by John D. Rockefeller. This fund is being administered by the Institute with the coöperation of the Central Petroleum Committee of the National Research Council. The work was done in the laboratories of the U. S. Geological Survey.

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Alaska,[1] including the region of the known oil seepages. Though of the

[1]One sample, the *Pseudomonotis* shale, comes from the valley of Yukon River.

five specimens submitted all but two are float, they are of unusual interest because they show the presence, in this little explored region, of "mother rocks" both rich and of widely diverse types.

The specimens were not large enough for the quantitative determination of their capacity to yield oils by distillation, but they were more than adequate for examination in the microfurnace where, on the stage of the microscope, thin sections were heated in an inert atmosphere to determine accurately the temperatures at which each commodity or fossil component of the organic deposit forming the rock yielded its contribution.

The specimens include

1. A rich boghead or alga coal.
2. A sedimentary rock made up almost entirely of the exines, or thick, fatty or waxy protective coverings of very large spores, this rock being very closely comparable with the "tasmanite" from Tasmania. It may be termed a spore rock.
3. A brown oil shale of high quality containing a great many spore exines, many of which are twisted.
4. A marine deposit of the general structure and characters of an ordinary oil shale or bituminous shale, which is, however, remarkable for the presence therein of a great many calcareous shells of a Triassic mollusk known as *Pseudomonotis*. For convenience this may be termed the *Pseudomonotis* shale.

The tests, though not quantitative, indicate that all but one of the samples are capable of yielding large amounts of oil on distillation. As was to be expected in view of the results of tests of many other bituminous shales and oil shales from different parts of the country, the microthermal study of these supposed mother rocks of petroleum shows conclusively that, notwithstanding the long time since these deposits were laid down, and the geochemical changes that have taken place in consequence of deep burial and disturbance of the earth's crust, amounting to steep folding of mountain-building type, the different kinds of visible fossil residues and the "groundmass" in each type differ from one another in chemical composition, though all are changed from their original composition. It is evident also that the organic commodities in the rock of one type differ in their temperatures of change, hence in their chemical composition, from those of another type. These indications of difference are noted somewhat in detail in the description of the behavior of the visible components of the different specimens when heated in the microfurnace.

Among the conclusions reached in the course of the examinations of the separate specimens are the following.

1. The thick cell walls, probably of fatty composition, in the algal colonies are the principal sources of the oils distilled from the boghead.

2. The spore exines of the spore rock are the principal sources of oil distilled from this shale.

3. On heating the canneloid shale, oil seems to be yielded by several visible components, or plant vestiges of different types, at different temperatures.

4. Distillates are yielded both by certain types of fossil remains and by the "groundmass" (solidified colloid biochemical products of decomposition), but at different temperatures and of different composition.

5. Finally, as with other sediments of organic composition that have been studied in the microfurnace, it is found that a larger yield of oil is indicated when atmospheric oxygen is wholly excluded from the furnace; also that the oil is of higher quality and that it is generated at different temperatures from those at which the volatile matter is given off when oxygen is present. These observations suggest that in any experimental or commercial retorting of these carbonaceous rocks, including both oil shales collectively and coals, advantages in both quality and quantity of distillates may be secured by excluding air as fully as possible.

Minor conclusions follow the more detailed descriptions of the tests.

Localities and Geologic Age of the Specimens

Boghead.—This specimen (26 A. S. 94) is reported to have been gathered as float near the head of Meade River, northern Alaska. As described by P. S. Smith and J. B. Mertie, the entire region tributary to Meade River is regarded as underlain by rocks of Upper Cretaceous or later age. Therefore, it is very unlikely that the specimen dates earlier than the Cretaceous, notwithstanding its resemblance to some of the Paleozoic bogheads both in external appearance and paleontologic characters. That it may have been brought into the Meade Valley by outwash from the Lower Cretaceous or older rocks on the south, or that it may have been redeposited, is possible but unlikely, notwithstanding the redeposition locally of Triassic chert as pebbles in conglomerates of Upper Cretaceous age in this region. Smith is of the opinion that, "as it is so unlike any material known in the Upper Cretaceous sequence, it is more likely to have come from some lower formation."

The sample consists of a small piece of nearly black, fine-grained rock resembling cannel coal. It is largely composed of colonies of *Reinschia*, described later in this report as ***Reinschia alaskana***, suspended in a black matrix or groundmass.

A specimen of nearly identical aspect and fossil composition, illustrated by R. Thiessen,[1] is said to have been found as float in the Colville River basin.

Spore rock.—Another specimen (24 A. S. 95), reported near the mouth of Meade River by C. D. Brower, of Barrow, Alaska, also is float, the source of which is not known. It is a rounded pebble similar in general aspect to the boghead, though lighter, and has evidently been rolled in course of transportation. It may be regarded with probable safety as coming from the basin of Meade River, and if so, as stated with reference to the specimen last mentioned, its age is probably Upper Cretaceous, though it may have been derived from Triassic or older rocks not yet seen in outcrop.

A float specimen (24 A. S. 51) of brownish-black thin-bedded shale is reported as having been found on Etivluk River, not far below the outcrop of the base of the Lower Cretaceous. Etivluk River is one of the headwater tributaries of Colville River.

The geologic structure in this area is complex, the beds being partly overturned and perhaps profoundly faulted, "but there seems to be small reason to doubt that the oil shale came from strata near the base of the Lower Cretaceous rocks or from sedimentary rocks farther upstream, all of which are at least as old as the Lower Cretaceous." It is stated that specimens resembling that submitted for examination occur plentifully in the area in blocks of varying shapes and sizes.

Both of the samples examined are of essentially the same fossil composition, consisting almost entirely of the golden-yellow fatty envelopes, or exines, of very large spores flattened into a dense tough brown deposit of very light weight. Probably both are from the same geological horizon. The Etivluk material was formerly regarded by some geologic explorers as a petroleum residue, an interpretation proved erroneous on microscopical examination. The specimen, which will be more fully described later, closely resembles the so-called "tasmanite."

Brown oil shale.—A specimen (25 A. S. 15), of cannel aspect, was found in place by Smith on Kivalina River, about 4 miles south of "Camp P." Here the contorted and nearly vertical shales are separated from ex-

[1] "Origin of Boghead Coals," *U. S. Geol. Survey Prof. Paper 132* (1925), pp. 121-37, Pls. xxvii-xl.

posures of Triassic cherts by 20-25 feet of broken rock and slide, so that the relations are not determinable, with consequent doubt as to whether the shale is part of the Triassic series or of the Lower Cretaceous rocks occurring very near the Triassic both on the east and on the west. The shales are regarded by the field geologist as "probably Lower Cretaceous," but possibly they are Triassic.

Pseudomonotis shale.—This type of supposed "mother rock" of petroleum consists of a slightly brownish-black, pitchy-looking matrix, obscurely stratified or even laminated, in which a great many gray lime shells of a bivalve belonging to the genus *Pseudomonotis* (*P. subcircularis*) are loosely embedded in layers, as shown in the photograph, Plate 8, Figure 15.

The specimen (25 A. Mt. 93) was collected by J. B. Mertie on Trout Creek, a small tributary stream flowing from the south into Yukon River a few miles above the mouth of Nation River. The age of the deposit from which the specimen was obtained is proved by the fossil shells to be Triassic. As shown by the description on a later page, the fragment is an oil shale, notwithstanding the rather anomalous occurrence of the marine shells in it. With respect to the occurrence of the shells, this deposit is similar to the oil shale (kukersite) exploited in Esthonia.

Purpose and Methods of the Study

All carbonaceous or bituminous rocks, including the so-called "mother rocks" of petroleum, that are of sedimentary origin are found, when examined under the microscope, to consist of two distinct types of organic matter. (1) The groundmass, commonly regarded by most chemists as "humic" or "ulmic" in nature, is the organic binder in the sediment, and consists of hardened colloids of the products, including fatty acids, et cetera, formerly in aqueous solution, of the biochemical decomposition of organic matter, in which are suspended microscopical and ultra-microscopical detritus of various plant cells and other products, sometimes termed "attritus." (2) Recognizable, well preserved, or more or less macerated and decomposed organic remains, such as spores of different kinds, pollen, algal colonies, vestiges of woody tissues, bast, cuticles, resin grains, wax scales, et cetera, all more or less enveloped and some, as the tissue and alga cells, infiltrated by the biochemical solutions of the groundmass. These microscopical plant parts and detrital fragments are ordinarily translucent and lighter colored than the brown or very dark groundmass, they being generally found to range from a very pale or corn-colored phase of yellow to golden-yellow, amber, yellow-

ish-brown, reddish-brown, and orange-, or darker brown. The prevailing colors vary from pronounced yellow through brassy tones to golden-yellow and orange-yellow.

The plan of study, of which the microthermal tests constitute the first part, includes the distillation in a specially constructed retort which provides uniform heating, under close control in an inert atmosphere and under pressure, of samples duplicating those examined in the microfurnace, in order to determine, (1) the relative amounts of distillates yielded by each commodity in the rock at its ascertained temperatures of change, and (2) the qualities imparted to the collective distillate by the commodity at its different temperatures of volatilization. As already stated, however, the Alaska samples submitted were too small for testing satisfactorily in a retort. It is obvious, nevertheless, that the observations made by means of the microfurnace itself are both interesting and of distinct importance. The field of investigation is essentially virgin ground, and the critical data secured promise to be of value not only as constants for economic application in attempts to utilize oil shale on a commercial scale for the production of substitutes for petroleum, but also in further research both on oil shales *per se* and on the origin of petroleum.

The microthermal records given in the following pages embrace the observations of the optically visible effects produced by heat on the various visible organic components of the different rocks. The data have been checked by scores of duplicate tests, always with the same results, the conditions of experimentation being the same, and the reactions described can be photographed, measured, and reproduced, provided the procedure is the same.

It is important to note that all the tests described in this paper are at normal pressures, and the time in no case exceeds four hours.

All tests were made on sections of the rock carefully ground to a thickness of only a few microns. The fragment of a section in view under the microscope is between 2 and 3 millimeters in diameter. Obviously, the yield of oil and gas given by so small a sample can not be subjected to chemical study, even by present microchemical methods of analysis.

Most important among the changes observed either in the groundmass or the fossil contents of the organic rock as viewed in the microfurnace is change of volume. This includes, (1) expansion—when groundmass begins to swell, and (2) contraction—shrinkage—ordinarily accompanied by darkening, which in the later stages, at least, reflects advancing carbonization. The first change may signify mole-

cular rearrangement or change of state: solid→liquid→gas; the second is due to loss of volatile matter formed under the influence of heat. The temperatures at which these changes are observed differ in different rocks. Further, the amounts of expansion or contraction also differ.

Since the visible fossil commodities in the rock differ more or less in composition one from another, as is indicated by differences in temperatures of change, including volatilization, and since all of them differ from the groundmass, from which they are distinct in some, at least, of their reactions, as well as in their aspect, the groundmass and the enveloped visible fossil bodies are described and discussed separately in the records of the tests.

Microscopical and Microthermal Examination of the Specimens

I. BOGHEAD FROM THE MEADE RIVER BASIN

DESCRIPTION OF THE ROCK

General physical characteristics.—In physical appearance the sample from Alaska resembles the typical Permian and Mississippian bogheads from Autun, France; New South Wales; Bathgate, Scotland, and other places. It is compact, brownish-black in color, conspicuously conchoidal in fracture, with satiny, almost silky sheen and a very fine texture. The streak produced on the ordinary mineralogical streak-plate is "mummy brown." The specific gravity, determined on a small piece, is 1.32.

Microscopical characteristics.—The examination of thin sections under the microscope shows that the rock is made up almost wholly of yellow and amber-yellow bodies, oval in shape, and of various sizes, ranging from 0.03 to 0.13 millimeters in diameter (Plate 1, Fig. 1), immersed or even suspended in a dark brownish-black organic matrix, the groundmass. The larger bodies are elongate and many are flat.

These yellow bodies are compound colonies of microscopical unicellular algae, each plant consisting of a small ovoid cavity filled with brownish "humic" matter surrounded by a very thick cell wall of gelatinous aspect, but actually fatty in composition. The individual cells or plants are cemented together to form the colony. They represent a species of the genus *Reinschia*, and resemble the colonies of the same genus found in the boghead ordinarily known as "kerosene shale" (Plate 1, Fig. 2), from New South Wales.

The groundmass is warm brown or, in some places, dark brown. The colonies are generally scarcely in contact with one another. Small fragments of plant tissue, and a few cuticles and spores also are found

scattered through the groundmass in different, but everywhere very small, amounts. As is readily seen from the photographs (Plate 1, Fig. 1, and Plate 2), the relative volume occupied by the colonies, as compared with the total rock, is variable. In some sections, and even in parts of a single section, they predominate over the groundmass; in others the groundmass constitutes the larger volume.

BEHAVIOR IN THE MICROFURNACE

When heated in the microfurnace in an inert atmosphere (helium), the Alaska boghead undergoes several changes which are indicated by change of color, dimension, or state of substance. It was expected on the basis of examinations of these and other rocks that the changes of the groundmass and of the algal colonies would be at different temperatures, showing that they differ in chemical composition. Actual observation of the boghead in the microfurnace confirms this assumption.

Groundmass.—Changes of the groundmass become apparent even at low temperatures. At 150°C.[1] it takes on warmer hues, as if it were slightly luminous. This warmth of color increases with the temperature, and at 200° the groundmass is distinctly luminous and has a reddish tinge. The reddish hues at temperatures about 250° are quite distinct and turn deeper with increased temperature. At 340° to 350° the whole section swells. At 370° the groundmass begins to soften and in places is more translucent. The softening is followed by shrinkage and darkening, indicating plainly that at this temperature the groundmass undergoes a chemical change, as a result of which some of the volatile substances are given off. As the temperature rises, the darkening of the groundmass increases, and at about 420° the groundmass is almost opaque and dull brown.

The "complete" carbonization of the groundmass takes place gradually, at temperatures above 500°. The exact temperature evidently depends partly on the time or rate of heating. The carbonized groundmass is dense black with a shiny luster, and appears very hard and rigid. The cell contents of the individual colonies leave black residues in place, and can be easily seen in the sections heated to high temperatures (Plate 2, Fig. 3).

Algal colonies.—The algal colonies appear unchanged up to 210° C., beyond which, between 210° and 215°, they begin to swell and continue to enlarge for some time, depending on the rate of heating. On approaching 300° they change in color; those that were yellow turn to amber, and the amber-yellow to orange. A second increase in volume takes place at

[1]All temperatures indicated are in degrees Centigrade.

340° to 350°. The darkening of the groundmass, following softening at 370°, is accompanied by a darkening of the colonies, possibly coincident, or possibly due to a flooding of the colonies by the melted groundmass. From 400° to 420° the colonies turn reddish and go from russet-red through wine red to brownish red. At 445° the colonies are brown; they have lost their transparency and luster, and appear to be fading on the dull opaque groundmass. However, a few degrees higher, they begin to grow lighter again, warm reddish hues reappear, fusion and swelling take place, and at 455° the swollen colonies rapidly, almost explosively, puff up, and the liquefied material of the cell walls volatilizes, leaving thin films of amber-colored waxy residue (Plate 2, Fig. 4, and Plate 3, Fig. 5).

The phenomenon of melting and volatilization is spectacular, and resembles the behavior of the kerosene shale of New South Wales, though differing in some respects. The yield of the oil in the case of the Alaska boghead appears to be smaller than in the specimens of the kerosene shale examined. Furthermore, judged by the small amount of the residue left and the speed with which the melted contents of the Alaska colonies volatilize, the composition of the oil formed from the latter is somewhat different from that from the Australian.

Effect of oxygen.—If even the slightest amount of oxygen is admitted to the microfurnace, the yield of oil decreases. The colonies shrink and darken at about 400°, and at 455°, instead of the ordinarily complete melting and volatilization, only a small amount of oil is given off, as the colonies continue to darken, become opaque and, at higher temperatures, carbonize.

CHANGES IN THE OPTICAL PROPERTIES OF THE ROCK

Both the colonies and the groundmass of the Alaska boghead are anisotropic and quite distinct in their optical properties. These properties are affected by temperature, and while it was not possible to determine the exact temperature at which changes take place, it is evident that some changes are gradual. The groundmass, which is optically less active, loses its birefringency at lower temperatures.

SUMMARY

1. The samples from Meade River, northern Alaska, represent a typical, relatively pure boghead, composed mainly of colonies of unicellular algae, loosely embedded in a "humic" or "ulmic" groundmass.

2. The view held in some quarters that these colonies are mere segregations or nodules of hydrocarbons is positively contradicted, and

any assumption that they are of inorganic nature is conclusively disproved.

3. When heated, both the algal colonies and the groundmass undergo changes which are quite distinct and well differentiated, as between algae and groundmass.

4. The most obvious change in the groundmass occurs at about 370° C., when the softened substance begins to shrink, darken, and give off volatile matter. On continued heating the groundmass forms a rigid, black, carbonized residue.

5. The tests indicate that the boghead from Alaska is capable of yielding large quantities of oil and gas. The algal colonies are the principal source of the oil distilled. They melt and volatilize at 455° C.

6. The examination indicates that in any attempt to utilize this rock on a commercial scale the yield of distillate will be very favorably affected if air or oxygen is excluded so far as possible from the retort in which the rock is heated.

7. Both the groundmass and the algal colonies have distinct optical properties, subject to definite changes with changes of temperature.

II. THE SPORE ROCK

DESCRIPTION OF THE ROCK

Physical characteristics.—The sample of spore shale from Alaska is dark brown, has a fine velvety texture, is finely laminated, soft, and can be cut with a knife as easily as a piece of soft, well seasoned wood. It gives a cinnamon streak, indicating that the fixed carbon content is not high. The specific gravity is only 1.005.

Microscopical characteristics.—Thin sections of the shale show that it is very purely organic, being almost entirely composed of brassy, waxy-looking spore exines. In cross section these exines appear as flattened rings in a dark "humic" groundmass, which also defines their inner walls. The large exines are macroscopic and mostly thick-walled, though some have fairly thin walls. The resemblance of the spore exines to *Sporangites huronensis*, and especially to the so-called *Tasmanites punctatus*, is evident from the photographs (Plate 3, Fig. 6, and Plate 4). A few exines of other, smaller spores are met, but they are quantitatively unimportant.

BEHAVIOR IN THE MICROFURNACE

Groundmass.—The groundmass in the sections studied is very limited in amount. It is visible in the center of the spore as a very thin, dark brown stripe, and it serves as the cementing material between the separate spore exines, binding them together in the mass.

The observations of the groundmass, as seen in the furnace, lack much detail, since at times it is hard to decide whether the changes noted are in the groundmass or in the spore exines, so little is the "humic" component of the rock. However, some changes in the groundmass are quite distinct. The luminosity of the spores, evident at 160° to 165°, appears to be shared by the groundmass as well. At 200° slight swelling occurs in the groundmass, and is accompanied by increased transparency of the latter. The luminosity continues to increase until, at 220°, the groundmass softens. At 252° some of the "humic" areas are fused and much darkened, and at about 400° the groundmass shrinks, becomes almost opaque in places, causing the spores to be more or less clearly separated. This is the point of loss of the greater part of its volatile matter.

Spore exines.—The first reaction noted in the spore exines is at low temperatures, 115° to 130°, slight swelling taking place. At 170° the swelling is more apparent. The changes in the structure of the substance at the temperatures of 180° to 186° are quite marked when watched under the microscope. Though not shown well in the photographs, it can be seen in Plate 3, Figure 9, that the surfaces of the exines are pitted and that their substance is lumpy in appearance. This granular structure is not permanent, for at temperatures above 200° the exines change again into an almost structureless mass (Plate 5, Fig. 10).

Darkening of the exines is not apparent until between 275° and 280°, when they turn nearer golden-yellow; and, as the temperature rises, they gradually change to amber-yellow and, finally, to orange. At 410° they are grayish. With increase of temperature, warmer hues return and the exines, though darkened, take on a warmer orange-brown color. The significance of these changes can be known only when a check sample is treated at this temperature in a retort.

Fusion of the exines takes place at 468° to 470°. The orange-brown substance of the spores begins to lighten, then it softens, and finally melts into a very plastic substance, which in turn liquefies, after which the substance of the exine remains for a time in a liquid state (Plate 6, Fig. 11). Volatilization by cracking seems to take place within a very short time, and the molten matter of the exine condenses into a viscous substance, which darkens, hardens, and finally carbonizes (Plate 6, Fig. 12). The cracking occurs at or imperceptibly above the temperature of melting, and if the section is chilled instantly at the melting temperature, the molten substance is almost entirely soluble in several organic solvents, such as benzol, toluol, pyridine, carbon tetrachloride, and

chloroform. The residue after cracking is only slightly soluble in benzol. The fused state may correspond with what McKee describes as an "intermediate stage" in the conversion of the organic matter ("kerogen") into oil.

Plate 6, Figure 11, shows rock after chilling at 470°, at which temperature the substance is becoming soluble. Flowage has taken place but does not show clearly in the photograph. The residue, just after cracking has begun, is shown in Plate 6, Figure 12.

The carbonization of the residue is essentially completed at about 575°, though the temperature has not yet been definitely determined.

If oxygen is admitted to the furnace the effect is quite similar to that in the boghead and the kerosene shale, that is, the yield of oil is considerably reduced and the amount of the carbonized residue is correspondingly larger.

CHANGES IN THE OPTICAL PROPERTIES OF THE ROCK

The spore exines and the groundmass of the shale exhibit very strong and distinct optical properties. With heating, the latter change, and at about 448° all the exines are isotropic. The groundmass loses its anisotropic properties at a lower temperature than the spore exines.

SUMMARY

1. The spore rock is similar to the so-called tasmanite, from Tasmania, and is almost entirely composed of spore exines, possibly macrospores of the lycopod order. It is very rich shale and should yield a large volume of gas and oil.

2. The most notable change in the groundmass takes place at about 400°, when it darkens, shrinks, and begins to carbonize. This is the temperature of probably greatest yield of volatile matter from this source.

3. The melting of the spore exines with the visible formation of oil occurs between 470° and 472°.

4. As the temperature approaches the melting point, the substance of the spore exines becomes soluble in the ordinary organic solvents. The degree of solubility decreases as soon as "cracking" takes place.

5. The experiments indicate that the yield of oil and gas decreases, if air or oxygen is admitted.

6. The optical properties of the groundmass and the spore exines change with change of temperature.

7. The change of organic matter from insoluble to soluble at temperatures near the melting point in these rocks suggests a series of interesting and possibly important economic experiments.

III. KIVALINA OIL SHALE

DESCRIPTION OF THE ROCK

Physical characteristics.—The samples are of two distinct phases, one, a typical oil shale, resembling particularly the Devonian black shale from Ohio; the other, resembling highly compressed and crumpled lignite, with slickensided surfaces.

Microscopical characteristics.—Under the microscope the difference previously noted is not so marked. The lignite-like samples have the same characteristics as the other, except the effects of folding and compression. The rock is composed of a warm brown, fine-grained groundmass with sparsely scattered golden-yellow spore exines (*Sporangites alaskensis*). In horizontal section the spores are disc-shaped with a distinct outer ring (Plate 7, Fig. 13). In some samples the inner part of the spore is gone and only the peripheral ring remains. In vertical section some spores are figure-eight shaped and resemble pretzels (Plate 7, Fig. 14).

BEHAVIOR IN THE MICROFURNACE

As noted in the description, the number of spores in the specimen from Kivalina River is limited, so that the presence of two or three at once in the very minute field of the microfurnace is not common.

Under increasing temperatures reactions are noted at an early stage of heating. Between 150° and 175° the groundmass begins to swell and punctations in the exines appear as pin holes. At 170° the spores are luminous. At 215° the groundmass begins to darken, but the spores appear unchanged. At 295°-300° another swelling of the groundmass is observed. Meanwhile the darkening of the latter progresses, until at 430° it is almost opaque.

At 440° the spores also begin to darken, and at 445° they fade out so as to be hardly distinguishable from the groundmass. However, at only a few degrees higher, 465°-468°, melting of the spores takes place. The oil formed from the spore exines is light yellow, and seems to volatilize rapidly without a large organic residue.

The groundmass turns gradually opaque, and between 520° and 530° it becomes quite opaque. If heated to higher temperatures it continues to lose volume, but the loss is not so apparent at the time of heating as after cooling, when shrinkage is very rapid and quite marked. At 570° the section is rigid and appears completely carbonized.

SUMMARY

1. The reactions produced by heat indicate clearly that the chemical composition of ***Sporangites alaskensis*** is different from that of the groundmass in which it is embedded.

2. Volatile matter is yielded probably in considerable volume by the groundmass, in which changes are noted in zones beginning at 150°, 215°, 295°, and 520°.

3. Melting and volatilization of the spore substance are observed at 468°, when light oil is formed, which quickly volatilizes.

Pseudomonotis SHALE

DESCRIPTION OF THE ROCK

Physical characteristics.—The ***Pseudomonotis*** shale, according to P. S. Smith, is widely distributed in the Triassic of Alaska. The rock is, however, almost everywhere represented by chert, black in color, with a typical chert fracture.

On superficial examination the sample submitted appears to be composed of shells of a bivalve, *Pseudomonotis subcircularis* (Gabb), characteristic of the Triassic of Alaska (Plate 8, Fig. 15), roughly distributed in layers.

Microscopical characteristics.—Thin sections show, even at low magnifications, that the micro-structure of the matrix of the shale is comparable with that of many other oil shales, such as those of the Green River formation. It is a dark organic deposit, in which the colloidal attrital groundmass, irregularly laminated, contains much matted débris of algal thalli of various sizes, some algal filaments, spore exines, sparsely distributed and mostly of small size, and, here and there, relatively large envelopes having the aspect of small *sporangia*.

Immersed in the organic matter there are, besides the shells, scattered small calcite crystals, minute glomerules of different sizes, apparently composed of marcasite, and innumerable extremely fine, largely submicroscopical particles, some of which seem to be inorganic in nature. The greater part of the matrix is rough-granular in aspect and, as viewed under high powers, apparantly contains much minute attrital plant débris. The thin sections of the rock are brownish, becoming pale golden-yellow where cut sufficiently thin except in the cross sections of the shells.

Many of the fragments of thalli seem to have been much macerated at time of deposition, so that they appear gelatinous when highly magnified. Probably much algal material was disintegrated to furnish this

attrital matter of the colloid. Some of the fragments are, however, dense, relatively thick, and sharply outlined (Plate 8, Fig. 16).

Any suggestion that the rock may have been originally a shell (*Pseudomonotis*) deposit subsequently penetrated by hydrocarbons seems to be precluded by the lamination of the organic sediments, the failure of solvents, such as chloroform or carbon tetrachloride, to extract more than the very small percentages ordinarily extractable from oil shales, and the rather small amount of distillate as compared with the amount of the organic matter.

Distillation tests made of a sample of the shale by E. T. Ericson, of the U. S. Geological Survey, in 1927, gave a yield of 28 gallons of crude oil per ton. The oil has high gravity and low setting point.

The shale, as can be seen from the distillation tests, is not rich. It is worthy of notice, however, that the rock used for distillation was somewhat weathered; probably fresh specimens would yield a little more oil.

BEHAVIOR IN THE MICROFURNACE

The differential effect of heat on the visible components of the *Pseudomonotis* shale is apparent when the rock is gradually heated in the microfurnace. At temperatures between 150° and 180° C., the whole section becomes more translucent and almost transparent; but as the temperature rises the rock darkens slightly and then remains without apparent change until the temperature approaches 215°-230°, when the section swells slowly to a slight extent, and the organic plant remains, whether fairly well preserved or highly macerated, become more prominent.

The groundmass slowly darkens at approximately 255°. In passing to 283° it darkens further, slight shrinkage (partial devolatilization) being noticed. At 314° further shrinkage and darkening of all parts of the section are observed. At temperatures between 350° and 360° the dark brown groundmass is semi-opaque, and the organic vestiges are orange and still translucent. With increased temperature the groundmass darkens progressively, and between 415° and 420° it becomes quite opaque, and further slight shrinkage, probably due to additional loss of volatile matter, takes place. However, on cooling, there is no perceptible diminution of volume and the total shrinkage will hardly exceed 4 per cent in the area of the section.

The organic remains, which at 215° become more prominent, stand out still more distinctly on the darkening background of the groundmass as the temperature rises. At 314° they also darken and change from yel-

low to orange, remaining translucent. In one of the tests slow melting of the supposed algal colonies was observed at 382°. In another, fusion of the bodies resembling spores was noted at 375°.

The melting and the fusion previously noted are quite distinct, though, because of the small amount of the organized tissues present in the unit area, the change of state is not as striking as it is in the boghead or the spore rock. However, it is very significant, as it indicates plainly that chemical distinction persists even in the highly macerated substances.

SUMMARY

1. In the *Pseudomonotis* shale, as in the other rocks, the changes in the groundmass take place at different temperatures from those in the spores and other fossil contents, thus proving chemical differences.
2. Fusion of the spores and melting of the supposed algal matter were observed at rather low temperatures, 373° and 382°, respectively.
3. Oil is seemingly furnished both by the organic remains and by the groundmass, but at different temperatures.
4. A relatively low yield of distillate from this rock as compared with other samples discussed seems to accord with the relatively small percentage of algae and spores in the organic matter, as well as with the lesser total organic matter.

GENERAL RESULTS

In all of the rocks examined the effect of heat on the groundmass becomes apparent at lower temperatures than on the visible fossil components.

Changes in volume of the section at definite temperatures are relatively small in the boghead and the *Pseudomonotis* shale as compared with the Kivalina shale, in which they are well marked. The groundmass of the boghead and the spore rock has a well defined temperature zone, in which softening and even fusion (in thes pore rock) are evident. The temperatures at which these take place, however, are very different. Thus in the spore rock softening is noticed at 220° and fusion at 252°, while, in the boghead, softening, with partial fusion, is observed at 370°.

These observations prove that although the reactions of the groundmass present many changes in common or in similarity, such as luminosity, change of volume and color, softening, gradual loss of volatile matter, and final carbonization of the residue, the reactions can not be identical. The groundmasses therefore differ one from another more or less in chemical composition. In each of the specimens the groundmass, if watched closely when heated in an inert atmosphere, can be distinguished from

that of the others by some particular reactions or temperatures at which changes take place.

The reactions of the fossil bodies in the microfurnace are quite distinct. The most outstanding is the visible formation of oil, and consequent volatilization. The temperatures of volatilization of the fatty algae in the boghead (455°), the spore exines in the spore rock (472°), Kivalina shale spores (468°), are rather close and indicate probable similarity in the oils. The melting points of the spores and the fusion points of the supposed algae (375° and 382°, respectively), the prevalent organic fossil residues in the ***Pseudomonotis*** shale, are considerably lower than those of the algae and spore exines in the other rocks, and sharply separate this rock.

From the observations and more detailed conclusions given in connection with the descriptions of the individual tests, certain relations and facts may be considered as reasonably established. Confirming previous tests of various mother rocks, the tests of the Alaska samples clearly show that:

1. The visible fossil plant entities, such as spore exines and the remains of algae, in any sample, have melting points distinct from those of the organic groundmass in which they are embedded. They, therefore, must differ in their chemical composition, and presumably in the hydrocarbons they yield whether in the retort or by normal geologic processes.

2. Differences in the temperatures of volatilization of the groundmass in different rocks are caused by differences in its composition in the different types of mother rock.

3. In the presence of atmospheric oxygen the yield of oil from the rock decreases noticeably.

4. It is possible that the groundmass components of the different rocks were originally more uniform in character and that the composition of some, at least, of the enveloped plant fossils, especially the spore exines, which now also differ from rock to rock, may have once been similar or even identical. The differences in their present composition, as shown by different points of softening, swelling, melting, and shrinkage, may be due to different stages in the progressive natural carbonization, both of the groundmasses and of the visible fossil entities.

5. In some "mother rocks" the source of the oil resides mainly in the included fossil plant entities, such as the colonies of fatty algae in the boghead, or the spore exines in the spore shale.

6. The view rather widely held by oil-shale engineers, in particular, that the oil distilled from "mother rocks" is produced from some more or less definite chemical commodity termed "kerogen," is obviously unsupported. Even where the oil is derived mainly from the groundmass, which, in general, in spite of differences, may be similar in composition from rock to rock, the validity of the kerogen theory is put seriously in question, not only by the variant melting points of the groundmass in different "mother rocks," but also by the differences in the behavior of the groundmass in the more advanced stages of its carbonization, at which stages in some rocks as many as three periods of shrinkage have been observed. These differences do not seem to be explained by differences in the stages of natural carbonization of the rock as found *in situ*.

7. The examination lends no support to conclusions reached by several German investigators of bituminous rocks that the organic configurations, such as the algal colonies and spore exines enveloped in the groundmass (shown in the photographs of *Reinschia* and *Sporangites*) are mere aggregates of bitumen or inorganic in nature.

8. The boghead from northern Alaska is a rich "mother rock," in which the main source of oil resides in the algal colonies; the spore rock is also a rich oil shale, large amounts of oil being generated from the spore exines themselves; the Kivalina shale, as indicated by its behavior in the microfurnace, is fairly rich, some, at least, of the oil being derived from the spores, and some from other fossil débris seemingly of an algal nature. The *Pseudomonotis* shale is not a rich shale, as is proved by retort tests, but in this rock the total content of organic matter is not large.

9. The oil shale deposits of very rich types in northern Alaska are probably restricted both in thickness and extent, but their occurrence in regions including areas of oil seepages is interesting. It is probable that environmental conditions attending the deposition of rich deposits were also favorable for the formation of leaner bituminous rocks which may well be widespread in this region.

The melting and volatilization temperatures of the different components of the various rocks, as here determined at normal pressures by means of the microfurnace, are suggested as favorable points for experiments in hydrogenation.

DESCRIPTION OF FOSSIL PLANTS FOUND IN SOME "MOTHER ROCKS" OF PETROLEUM FROM NORTHERN ALASKA

DAVID WHITE

Reinschia, Bertrand and Renault, 1892.
Bull. Soc. Hist. Nat. d'Autun, Vol. V, p. 172.
Reinschia Alaskana, n. sp., D. W. Plate 1, Figure 1.

Cell cavities small, distant, very narrowly ovate, length nearly 2½ times breadth, rounded at the base, and deeply immersed in the thick fatty deposit of the coalesced cell walls.

The flattened compound colonies of these one-celled algae agree in their irregular, complex, somewhat invaginate and mammilate configuration, and in the deeply buried, slightly pyriform lumina, with the genus *Reinschia*, though the aggregates are in general much smaller than in *Reinschia australis*, the type species of the genus,[1] which is shown in Plate 1, Figure 2. The aspect and size of the cell lumen are very poorly shown in Plate 1, Figure 1. The boundaries of the enormously thickened "fatty" cell walls, which are the principal source of the oil in this specimen as well as in the Australian kerosene shale, are not well defined on account of the imperfect state of preservation.

As with some of the Australian specimens, the colonies, as seen both in the vertical and the horizontal sections, appear to be hardly in contact. They seemed to be largely, if not wholly, suspended in the very dark brownish-black groundmass, or "ulmic" colloidal solution of the products of the biochemical decomposition of other colonies and especially other less resistant organisms. Doubtless the colloid contained much fatty acid matter. The amount of attrital matter visible at moderate magnifications is very small.

It is interesting to notice that the *Reinschia* in the specimen from the Meade River basin is in close agreement as to size, arrangement, and cell details with the "yellow bodies" in the boghead from the Colville River basin, Alaska, illustrated by R. Thiessen in his paper on the "Origin of

[1] C. E. Bertrand and B. Renault, *Bull. Soc. Hist. Nat. d'Autun*, Vol. 5 (1892), p. 172.

the Boghead Coals."[1] Neither the exact locality nor the geological formation from which came the material illustrated by Thiessen are known, but, in view of the rarity of torbanites, or bogheads, and the seeming identity of the plant species revealed in these specimens, it is probable that both his specimen and that contributed by Smith, also from the Arctic slope of Alaska, came from the same geological formation, if not from actually approximate geographical sources.

In his paper, just mentioned, Thiessen points out the close similarities not only between the different forms of fatty algal colonies described as *Pila* and *Reinschia*, but between their detailed cell structures and arrangement. Further, he demonstrates in great perfection the identical nature of these organisms and of the living alga to which he gives the name *Elaeophyton coorongiana*.[2] This alga, which inhabits the saline lakes of South Australia, is not only responsible for the qualities, but also makes up the greater part of the recent bituminous deposits known as coorongite. Notwithstanding, however, the close resemblance and very evident genetic relationships between the living Australian plant and Paleozoic forms from Scotland and France described as *Pila*, it seems to the writer likely that in view of the mode of development of the compound colonies, with large interiors occupied by blank cells, the living *Elaeophyton* is probably more closely related to *Reinschia* than to *Pila*, which is characterized in general by smaller, more rounded colonies, with relatively large plant cells, less deeply immersed, and more distinctly prismatic in form.

In the paper by Thiessen, already cited, he describes and illustrates bogheads, from various regions, containing principally *Pila* or *Reinschia*. Among these, the specimen from the oil-shale series of Mississippian age at Bathgate, Scotland, shown in his Figure B, Plate 36, evidently belongs to the genus *Reinchia* (which is of Permian age both in New South Wales and Brazil), rather than to *Pila scotica* Renault. It differs from the latter by its smaller, pyriform, very large and complexly folded colonies, and less irregularly placed cells. Accordingly, the specimen from Bathgate, which represents a distinct species, may appropriately be designated as *Reinschia thiesseni* n. sp.

Among the fatty algal colonies comparable to *Reinschia alaskana* it may be noted that *Reinschia capensis* Renault is distinguished by its

[1] *U. S. Geol. Survey Prof. Paper 132* (1925), pp. 121-38. (See Plate 38, Fig. B, and Plate 39, Fig. A.)

[2] *Op cit.*, p. 126, Plates 27, 28, 29, 30, and 31.

smaller size and very much larger plant cells. In the genus *Pila*,[1] the forms approaching most closely to the plant in hand are *Pila liassica*[2] Renault, which has much larger plant cells, and *Pila kentuckyana* Renault,[3] which has much smaller colonies, with relatively much larger cells.

The algal nature of *Reinschia* and *Pila*, which has been strenuously opposed by several paleobotanists, and more recently by students of the petrology of coal, has been proved beyond all doubt by Thiessen in his report on the "Origin of the Boghead Coals," though the systematic position both of the living *Elaeophyton* and its unmistakably close fossil relatives, included in *Reinschia* and *Pila*, among the algae is not yet fully determined. They may belong to the *Croococcaceae*. In the examination of this question, attention should be given to *Gloecapsamorpha*, which, as described by Zalessky,[4] comprises the greater part of the rich beds of kukersite, the oil shale of Silurian age in Esthonia; the *Botryococcus braunii* described by Zalessky[5] from the Lake Balkash region in Turkestan; the recent deposits, also described by Zalessky,[6] from Lake Bieloe at Tver in Russia, and the n'hangellite,[7] a recent deposit found in Portuguese East Africa. It is likely that deposits of comparable origin and composition, though inconspicuous and insignificant in volume, are to be found in regions of the alkaline lakes of the western United States.

The results of chemical and distillation tests of coorongite are given in the report by Thiessen, and chemical analyses, with distillation determinations of bogheads and of recent deposits, may be found in the papers by Renault and Höfer as well as in the other papers cited.

Fatty algae of the types *Reinschia*, *Pila*, and *Elaeophyton* are pre-eminently important for their yield of oils on distillation. In general,

[1] "Sur quelques microörganismes des combustibles fossiles," *Bull. Soc. Ind. Min. St. Etienne*, 3d ser., Vol. 13 (1899), Pl. 20, Figs. 5-12.

[2] *Op. cit.*, p. 985, Pl. 18, Figs. 9-18.

[3] *Op. cit.*, p. 1032, Pl. 23, Figs. 4 and 7 B.

[4] M. D. Zalessky, "Sur le sapropelite de l'age silurien formé par une algue cyanophycée, *Soc. Paleont. Russie*, Annuaire, Vol. 1 (1916), pp. 25-42.

[5] "On the Nature of *Pila* of the Yellow Bodies of Boghead and on Sapronel of the Ala-Kool Gulf of the Lake Balkash," *Bull. Com. Géol.*, Vol. 33 (Petrograd, 1914), pp. 495-507.

[6] *Soc. Paleont. Russie*, Annuaire, Vol. 1 (1916), pp. 25-42.

[7] L. A. Boodle, "N'hangellite and Coorongite," *Roy. Bot. Gardens, Bull.* 5 (Kew, 1907), pp. 146-51. Anonymous, "Report on a Sample of N'hangellite from Inhambane, Portuguese East Africa," *Bull. Roy. Bot. Gardens* (Kew, 1907), pp. 151-53. See, also, Hans Höfer, *Das Erdöl*, 4th ed. (1922), p. 263.

all deposits containing such algae are rich in oil, the oil being found to increase both in quantity and quality (except where too far carbonized) as the algae increase in number and in perfection of preservation; the bogheads like torbanite, in which they make up nearly the entire rock, being found to yield as high as 170 gallons of oil to the ton of rock.

The specimen communicated by P. S. Smith (26 A. S. 94) was found as float in the upper Meade River valley. It is thought to have probably been derived from beds of Lower Cretaceous or possibly from beds of earlier age. There is little doubt that the float specimen "from the Colville River Basin," figured by Thiessen, is of the same age. Possibly it is from the same horizon and even the same locality.

Sporangites, Dawson, 1863.
Can. Nat., Vol. 8, p. 454.
Sporangites Alaskansis, n. sp., D. W.
Plate 7, Figures 13 and 14.

Large envelopes without apparent crests, now flattened lenticularly, measuring .175 mm. in diameter when flattened, generally circular, ordinarily exactly circular, in middle section, many twisted slightly or invaginated, with thick wall consisting of an inner layer, commonly orange-yellow, about one-third of the total thickness of the entire envelope, and evenly punctate or perforated from within with moderate closeness by minute pores. Outer envelope golden-yellow, ordinarily more or less corroded, with spongy or corroded surface, or even entirely removed, or, where only slightly decomposed, appearing with irregular pentagonal mesh, as though built of thick-walled, radially placed, short pallisade cells in one layer.

The envelope, where not macerated, is clear-cut, with smooth edges in cross section, and ordinarily exhibits a more or less distinct trace of the double layer, with little or no appearance of pores. Where, however, decomposition was further advanced at time of burial, the inner surface is regularly though minutely punctate and the outer surface plainly corroded. Not uncommonly the outer zone is entirely removed, leaving the inner band with outer surface rough.

It is evident that the disintegration of the spores, unknown quantities of which have undoubtedly disappeared through biochemical decomposition, has contributed largely, at least, to the "attrital" colloid, which accordingly may be assumed to have inherited special chemical characters from this source.

A few smaller spores are seen, and many thalloid remnants visible in the vertical sections appear as thin dark-brown patches in the hori-

zontal sections. The lamination of the rock is not strongly marked, the specimen being somewhat canneloid in aspect.

As already stated, the stratigraphic relations of the "brown oil shale" at the locality in the Kivalina basin are not definitely known, but it is believed that the oil shale is Lower Cretaceous in age or possibly older.

Sporangites arctica, n. sp., D. W.
Plate 4, Figures 7 and 8.

Extraordinarily large, relatively thin-walled exines, .375 mm. long when flattened, with thick walls, apparently without crest, and of nearly uniform thickness throughout; smooth, without ornamentation.

As shown both in vertical and horizontal sections in Plate 4, the specimen from the Etivluk basin is almost entirely made up of the collapsed and matted sporangia of this species. Most of the exines are brassy yellow, though some, evidently more macerated, are rusty yellow. In certain of the layers they are well preserved, but in others they are plainly corroded or even shredded. In a thin zone of the shale the less disintegrated exines appear to run together, as though slightly gelatinous in aspect, probably due to a stage of maceration. Relatively little attrital matter is present, even in the layers of more noticeable decomposition. Thin ulmic streaks, generally not more than a fine line in width, separate the exines and define the interiors. Very little trace of inorganic matter is noticeable, though a few small spores, together with fragments of algal thalli and small sacs, possibly the envelopes of eggs, are sparsely present. The deposit, which is remarkably pure, is nearly free from visible pyrite.

Both in size and aspect these spore exines, which so fully make up the rock matter, closely resemble not only the exines, but the aggregate deposit known as "tasmanite."

A specimen of the spore rock (24 A. S. 95) was found as float near the mouth of Meade River, Alaska. Another, more massive, but essentially identical in characters, was found, also as float, near Etivluk River, one of the head tributaries of Colville River. Both are almost certainly from the same formation, and are probably of Lower Cretaceous age.

PLATE 1

FIG. 1.—Boghead from Meade River, northern Alaska. (D. W. 1927-47.) (26, A. S. 94.) Vertical section. 225 diameters. *Untreated*

The light spongy bodies are colonies of one-celled algae (*Reinschia alaskana*, n. sp., D. W.) consisting mainly of fatty deposits lining the original plant cells, which are imperfectly indicated by dark spots within the outlines of the spongy bodies.

They appear as translucent yellow and golden-yellow in the section. The dark substance forming the background of the photograph is the colloidal groundmass. Besides the algal colonies it contains a few woody vestiges and small spores. As seen in many bogheads, the alga colonies appear scarcely in contact one with another, being apparently suspended in the colloidal solution.

The structure of the colonies of the *Reinschia* type is better shown in the Australian boghead photographed as Figure 2, for comparison. The difference in aspect of the colonies shown in Figure 1 and Figure 2 is due both to the smaller plant cells in the Alaska alga, and the state of preservation of the colony.

FIG. 2.—Boghead from Wolgan Valley, Newnes, New South Wales, Australia. Vertical section. 225 diameters. *Untreated*.

The individual cells in the compound colonies of *Reinschia australis* which form the light-colored spongy masses in this rock appear as dark ovate or pear-shaped spots. Originally they were fully immersed in the colony, but slight maceration and decomposition of some of the colonies have partly removed the peripheral covering. The dark color of the original cell cavities is due to impregnation by the colloidal groundmass solution. Notice the relatively small quantity of the groundmass, which serves as binding matter between the colonies.

The specimen represents a boghead capable of yielding by distillation about 170 gallons to the ton.

PLATE 2

FIG. 3.—Boghead from Meade River, northern Alaska. (D. W. 1927-47.) (26 A. S. 94.) (T. S. Exp. No. 211.) Vertical section. 225 diameters. *Heated to 825° C.*

In this section, which has been heated to 825° C., the algal colonies have volatilized, leaving light patches (voids) made grayish by black granular residue in specks and films. The residues of the so-called "ulmic" matters impregnating the cell cavities of the algae are seen as small black spots—carbonaceous residues—within the spaces formerly occupied by the colonies.

The groundmass in an advanced stage of carbonization is shiny black.

FIG. 4.—Boghead from Meade River, northern Alaska. (D. W. 1927-37.) (26 A. S. 94.) (T. S. Exp. No. 209.) Vertical section. 210 diameters. *Heated to 455° C.*

Photograph showing the aspect of the colonies (light) at the moment of melting. Notice that the colonies are puffed and fleecy in texture.

PLATE 3

FIG. 5.—Boghead from Meade River, northern Alaska. (D. W. 1927-47.) (26 A. S. 94.) (T. S. Exp. No. 203.) Vertical section. 210 diameters. *Heated to 460° C.*

This photograph shows the colonies (light spots in the photograph) of *Reinschia alaskana* almost devolatilized, leaving thin waxy residues. Small oval dark spots mark residues of "ulmic" matter in the cell cavities. Compare Figure 5 with Figures 1 and 4.

FIG. 6.—Tasmanite, Latrobe, Tasmania. (D. W. 1927-7.) Vertical section. 210 diameters. *Untreated rock.*

In this section, which is included for comparison with the Alaska spore rock shown in Figure 7, the collapsed and flattened envelopes or exines of the gigantic spores, *Tasmanites punctatus* Newt., are distinctly seen, though many of them are partly macerated.

PLATE 4

FIG. 7.—Alaska spore rock, Meade River, northern Alaska. (D. W. 1927-48.) (26 A. S. 95.) Vertical section. 210 diameters. *Untreated rock.*

In this photograph some of the collapsed and flattened exines of *Sporangites arctica*, n. sp., D. W., are very distinctly seen. Not a few are buckled or doubled at the end, as is shown at several places in the figure. Note that in this untreated

vertical section not only are the opposite walls of the spore exine nearly if not quite in contact, but also the spores are nearly in contact one with another, the quantity of the groundmass, the binder of the rock, being relatively small.

FIG. 8.—Alaska spore rock, Meade River, northern Alaska. (D. W. 1927-48.) (26 A. S. 95.) Horizontal section. 225 diameters. *Untreated rock.*

In this section, which is cut horizontally, the circular form of the flattened spores (*Sporangites arctica*, n. sp., D. W.) here seen slightly obliquely, is indicated by the arcs of circles which show nearly half the periphery of some of the exines. (See the exines on the upper right.) The light color of the entire field is due to the translucency of the golden-yellow exines.

PLATE 5

FIG. 9.—Alaska spore rock, Meade River basin, northern Alaska. (D. W. 1927-48.) (26 A. S. 95.) (T. S. Exp. 187.) Vertical section. 210 diameters. *Heated to 183° C.*

In the section at 183° the substance of the spore exines is more refractive, giving them an aspect of convexity of the cut edges, while the dark groundmass more clearly defines both the cavity of the collapsed spore and the narrow intervals between the spores.

The slight maceration or decomposition of the outer walls of some of the exines gives the latter a corroded or ragged aspect.

FIG. 10.—Alaska spore rock. Meade River, northern Alaska. (D. W. 1927-48.) (26 A. S. 95.) (T. S. Exp. 192.) Vertical section. 210 diameters. *Heated to 448° C.*

In this view of the section, after heating to 448°, the spore exines are somewhat darker and smoother in aspect. Shrinkage of the binding groundmass has produced cracks or irregular tears, showing as ragged, elongate, narrow white patches parallel with the spores.

PLATE 6

FIG. 11.—Spore rock. Meade River, northern Alaska. (D. W. 1927-48.) (26 A. S. 95.) (T. S. Exp. 201.) Vertical section. 210 diameters. *Heated to 470° C.*

Photograph of the vertical section, in which heating has been interrupted at 470° C., the moment of rapid melting. Notice the contorted and somewhat disorganized aspect of the exines, between which the groundmass is more evident.

FIG. 12.—Spore rock. Meade River, northern Alaska. (D. W. 1927-48.) (26 A. S. 95.) (T. S. Exp. 198.) 210 diameters. *Brought up to 470°-472° C. and held for 30 seconds.*

The dark zones represent residues of the wasted spore exines piled in windrows by the ebullition of the oil. The large light spaces, from which the exines were driven, are either left void or flecked by gray spots and brown films formed by the cracking of the oil.

PLATE 7

FIG. 13.—Oil shale. Kivalina River, northern Alaska. (26 A. S. 15.) Horizontal section. 225 diameters. *Untreated.*

Horizontal section of oil shale showing a single spore exine, *Sporangites alaskansis*. n. sp., D. W. In this photograph the zoning of the wall of the exine in two layers is visible, especially in the narrowly oval section of the inverted wall of the same exine. Some of the twisted or inverted exines of spores in this shale exhibit pretzel patterns when seen in cross section, as is illustrated, with lower magnification, in Figure 14.

The groundmass appearing black in the photograph contains some attritus.

FIG. 14.—Oil shale. Kivalina River, northern Alaska. (26 A. S. 15.) Vertical section. 112 diameters. *Untreated.*

Vertical section of the Kivalina oil shale showing several of the large spore exines (*Sporangites alaskansis*) appearing pretzel-like in the transsection. The zonation of the exine is seen in the specimen on the lower right. The white blotches appearing in

the dark groundmass are due principally to the refractivity of inorganic matter in the rock.

PLATE 8

FIG. 15.—*Pseudomonotis* shale. Trout Creek, near Nation River, Alaska. (25 A. Mt. 93.) Specimen in natural size. *Untreated.*

View of horizontal or bedding plane aspect of the shale, showing shells of the mollusk, *Pseudomonotis subcircularis*, in natural size. The line *a-a* marks the point at which the vertical section shown in Figure 16 was cut.

FIG. 16.—*Pseudomonotis* shale. Trout Creek, near Nation River, Alaska. (25 A. Mt. 93.) Vertical section. 225 diameters. *Untreated.*

In this enlarged view of the vertical section of the same shale is seen the organic dark matter which forms layers in the vertical space between the layers of calcareous bivalve shells. A considerable amount of inorganic matter, mainly grains of calcite, is suspended in the organic colloid. Several lenticular, flocculent bodies, probably more or less rounded in ground plan, may be algal colonies, which, however, do not appear to be common in this organic sediment.

The shells are those of *Pseudomonotis subcircularis* (Gabb), which is characteristic of the Triassic of this region.

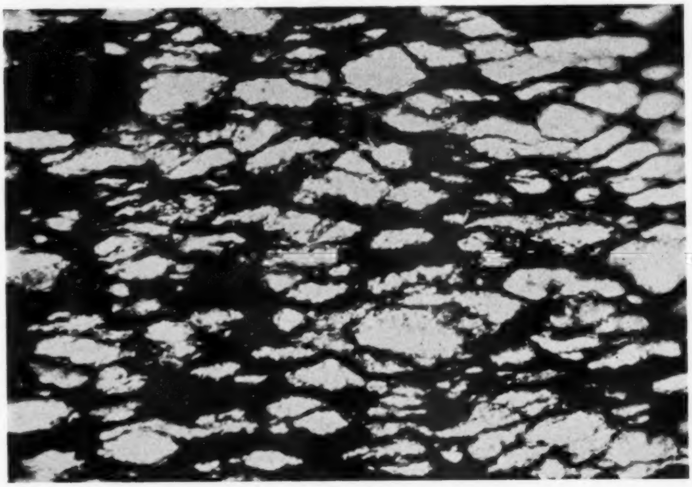

FIG. 1.—Boghead from Meade River, northern Alaska. (D. W. 1927-47.) (26, A. S. 94.) Vertical section. 225 diameters. Untreated.

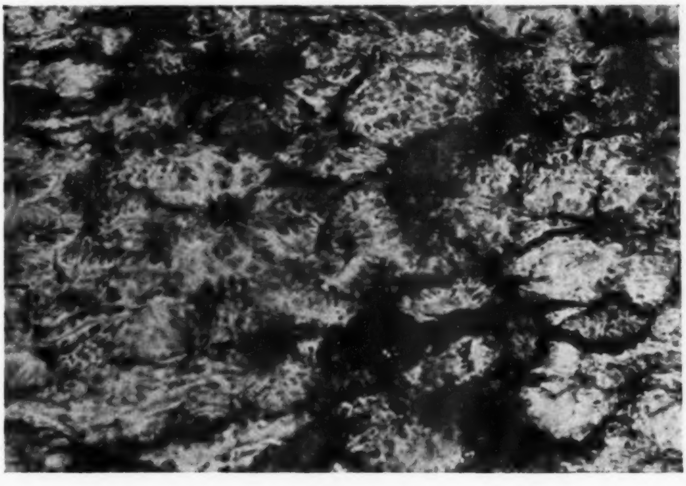

FIG. 2.—Boghead from Wolgan Valley, Newnes, New South Wales. Vertical section. 225 diameters. Untreated.

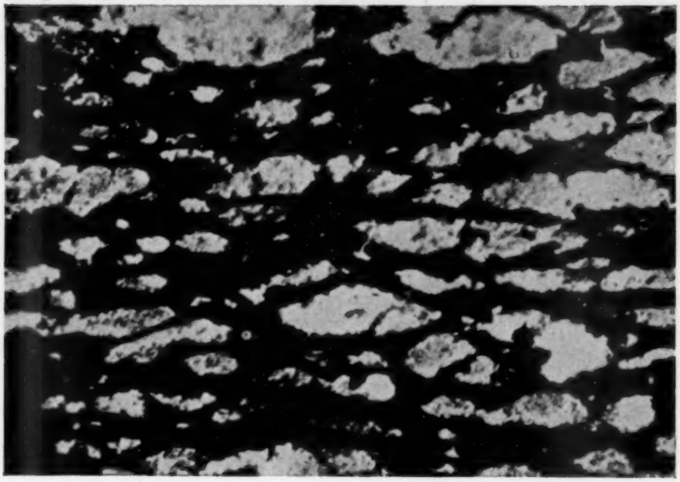

FIG. 3.—Boghead from Meade River, northern Alaska. (D. W. 1927-47.) (26 A. S. 94.) (T. S. Exp. No. 211.) Vertical section, 225 diameters. Heated to 825° C.

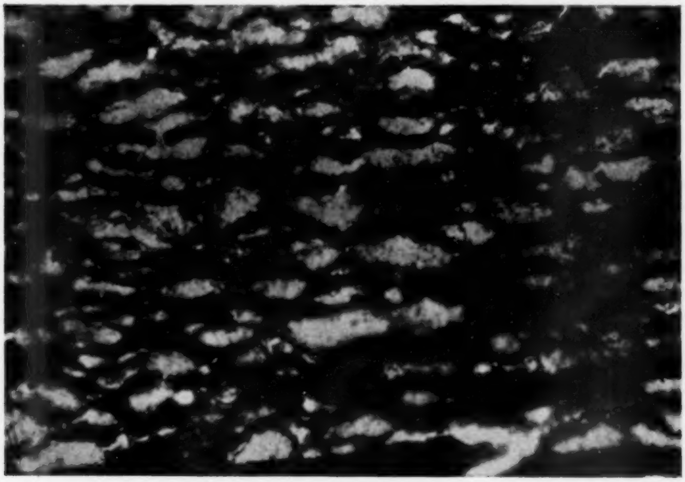

FIG. 4.—Boghead from Meade River, northern Alaska. (T. S. Exp. No. 209.) Vertical section. 210 diameters. Heated to 455° C.

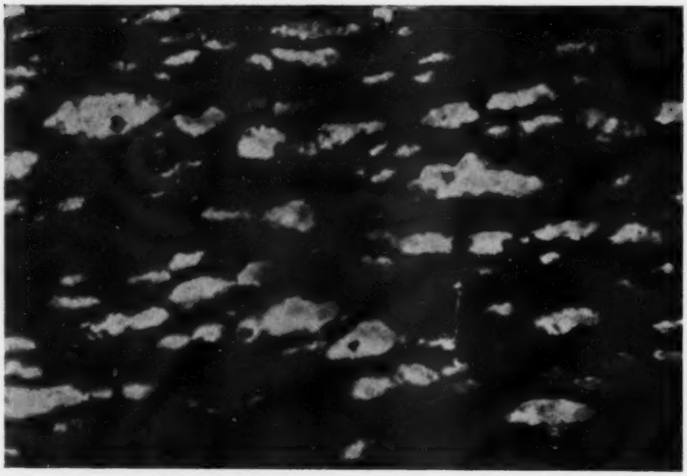

FIG. 5.—Boghead from Meade River, northern Alaska. (T. S. Exp. No. 203.) Vertical section. 210 diameters. Heated to 460° C.

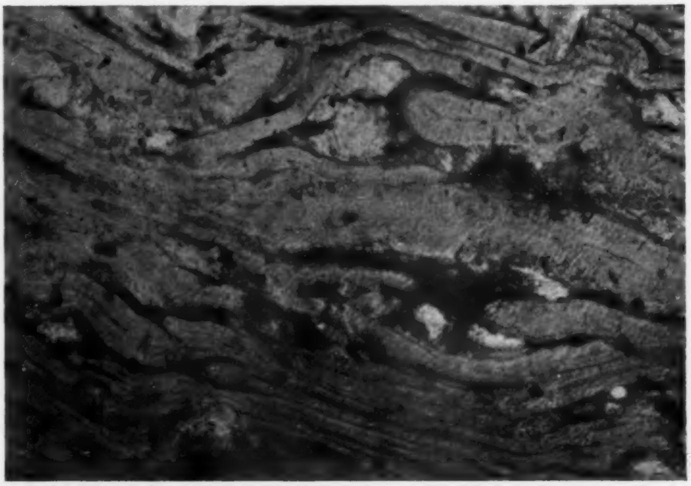

FIG. 6.—Tasmanite, Latrobe, Tasmania. (D. W. 1927-7.) Vertical section. 210 diameters. Untreated rock.

FIG. 7.—Alaska spore rock, Meade River, northern Alaska. (D. W. 1927-48.) (26 A. S. 95.) Vertical section. 210 diameters. Untreated rock.

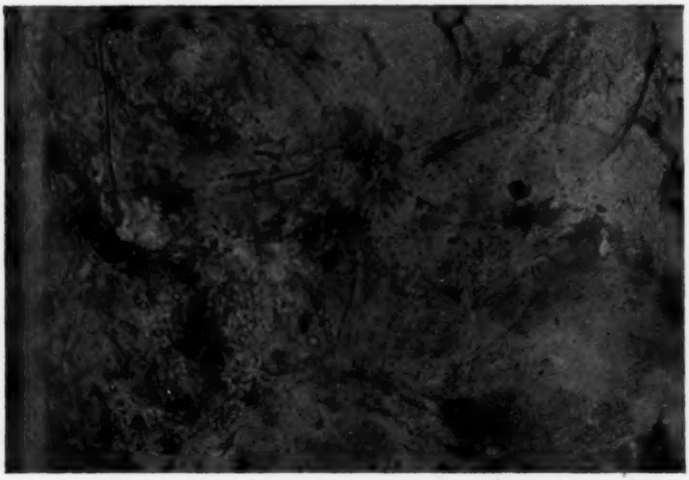

FIG. 8.—Alaska spore rock, Meade River, northern Alaska. Horizontal section. 225 diameters. Untreated rock.

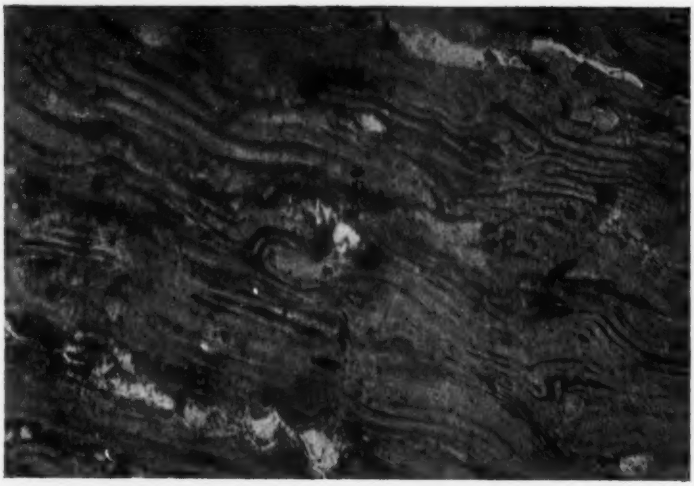

FIG. 9.—Alaska spore rock, Meade River, northern Alaska. (T. S. Exp. No. 187.) Vertical section. 210 diameters. Heated to 183° C.

FIG. 10.—Alaska spore rock, Meade River, northern Alaska. (T. S. Exp. No. 192.) Vertical section. 210 diameters. Heated to 448° C.

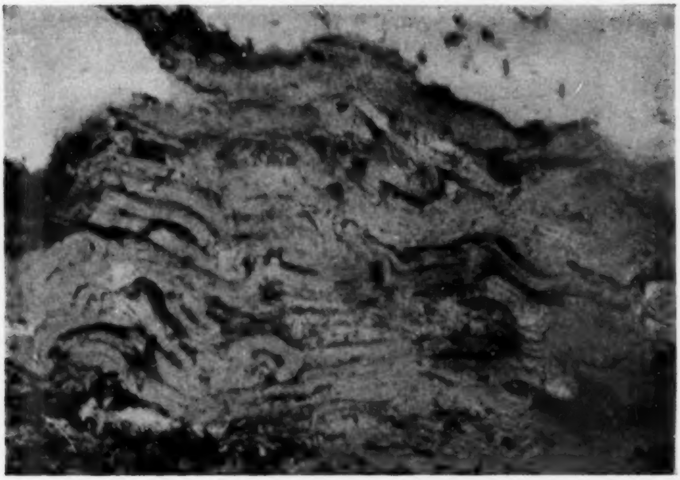

FIG. 11.—Spore rock, Meade River, northern Alaska. (T. S. Exp. No. 201.) Vertical section. 210 diameters. Heated to 470° C.

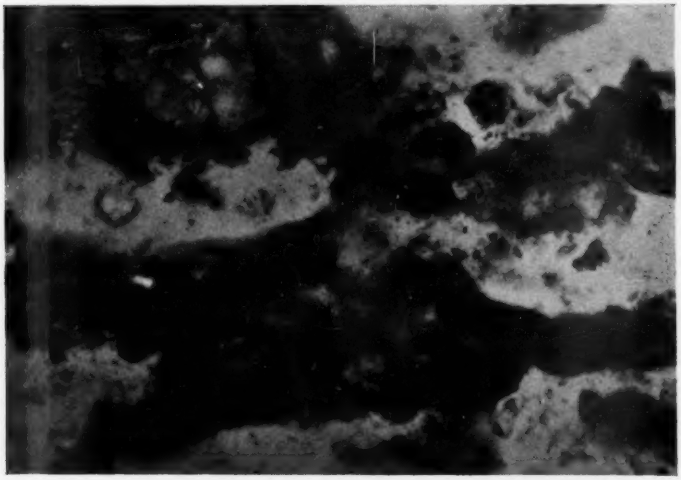

FIG. 12.—Spore Rock, Meade River, northern Alaska. (T. S. Exp. No. 198.) Vertical section. 210 diameters. Brought up to 470°-472° C. and held for 30 sec.

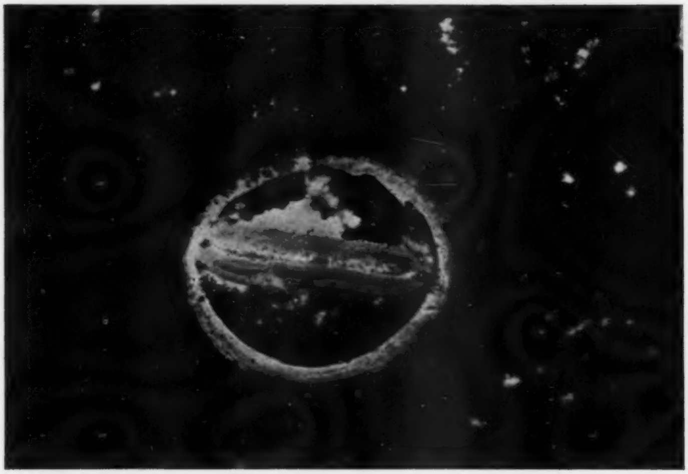

FIG. 13.—Oil shale, Kivalina River, northern Alaska. (26 A. S. 15.) Horizontal section. 226 diameters. Untreated.

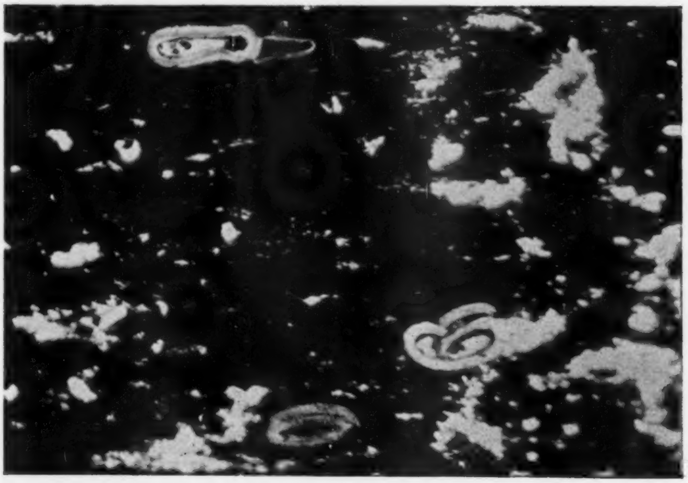

FIG. 14.—Oil shale, Kivalina River, northern Alaska. (26 A. S. 15.) Vertical section. 112 diameters. Untreated.

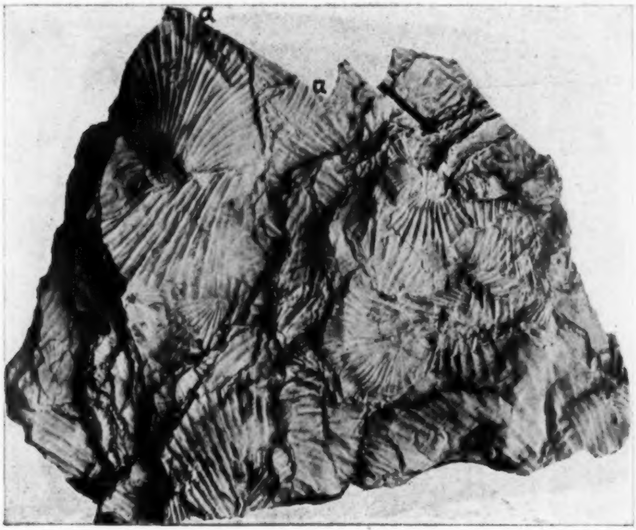

FIG. 16.—*Pseudomonotis* shale, Trout Creek, near Nation River, Alaska. (25 A. Mt. 93.) Specimen in natural size. Untreated.

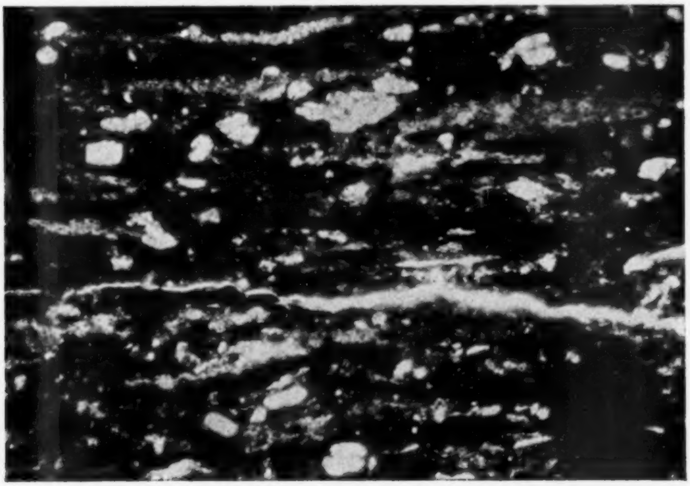

FIG. 16.—*Pseudomonotis* shale, Trout Creek, near Nation River, Alaska. (25 A. Mt. 93.) Vertical section. 225 diameters. Untreated.

GEOLOGICAL NOTES

DISCOVERY OF NEW POOLS

The editor believes that our *Bulletin* is a most suitable publication wherein to record the facts concerning the discovery of new oil or gas pools. There is no reason why credit should not be given where credit is due. Will members kindly bear in mind that, when a new pool is definitely established, we want a correct record of the name and location of the discovery well, the name of the individual or company drilling this well, the method (surface or subsurface geology, torsion balance work, seismographic work, et cetera) by which the location was selected, the person or persons who chose the location, and any other facts pertaining to the discovery; also the depth and name of the pay sand, the initial production, et cetera. Notes of this kind are often of great value for reference in later years. They should be submitted for publication under the heading, "Geological Notes." Subsequently, as pools are developed by drilling, but before they have been completely outlined, brief descriptions of their structural and stratigraphic features and the relations of these features to oil accumulation will be welcome for this department.

F. H. L.

LET US HAVE MORE "GEOLOGICAL NOTES"

We have observed a very decided falling off in the number of "geological notes" contributed by our members during the last year and a half. In Vol. XI (1927), there were 29 of these short articles published; in Vol. XII (1928), there were 19; but in the first five months of 1929, we have had only 5.

This department of the *Bulletin*, "Geological Notes," furnishes an outlet for brief notices and descriptions of geological facts and suggestions of real interest, but generally of such a nature that they are inappropriate for long, formal articles. They may be subjects of limited scope or possibly there may not be sufficient time for their more thorough treatment.

Here is an opportunity for members to add vitality to the *Bulletin*. Let us have ideas from your experiences. Tell the rest of us about in-

teresting geological features which you see in your work. Give us some facts on problems which you are studying, or suggest problems which you would like to recommend for investigation. Let us have constructive thoughts, and let us have your criticisms.

F. H. L.

A PRELIMINARY CONTRIBUTION TO THE BENTON PALEOGEOGRAPHY OF EASTERN COLORADO[1]

The prevailing idea of conditions in the Rocky Mountain region during Cretaceous time seems to be that of complete submergence with diastrophic quiet, though possibly a slow settling or sinking of the entire area. The present structural features are usually considered as originating in post-Cretaceous time.

The writers question these ideas and in this preliminary paper[2] will endeavor to present evidence to justify their opinions.

The data employed are based on information supplied by the Midwest Refining Company, by John H. Wilson, and by personal observations in the field.

The writers do not believe that during Benton time there was as extensive and complete a submergence of Colorado as is generally assumed. It seems more probable that the submergence did not reach its maximum extent until after the beginning of Niobrara time. During the early Benton there were many land masses which at first supplied some sediment, and later, when subsidence was more complete, served as barriers to deflect currents and modify deposition or remained at the profile of equilibrium for considerable intervals of time.

These land masses occupied the sites of still older masses which were uplifted in the late Mississippian or in the early Pennsylvanian. It is interesting to notice that in general outline, and even in some of the details, these lands closely followed the general outline of the present Front Range and Wet Mountains, structures which are generally considered as having originated during the Laramide revolution or even later.

[1]Presented before the Southwestern Section A. A. A. S. at Albuquerque, April 24, 1929.

[2]Mr. Johnson is making a study of the Benton formations in eastern Colorado and has several papers in preparation which discuss in detail the areas mentioned here.

Mr. Johnson's attention was first directed to this in 1927 when studying the Wet Mountains, where Dakota and Benton overlap older rocks, to the crystallines along the southern end of the range, and the Benton formations become sandy and carry a rich fauna of near-shore forms. In general, in the Pueblo, Walsenburg, and Spanish Peaks quadrangles, the Benton formations contain many local sandstones and tend to become somewhat sandy, suggesting an approach to the shore line.

Cross,[1] in the Pike's Peak folio, states that the Benton shows considerable variation in thickness, and at one place, in the southern part of the quadrangle, only a few feet of sediment separates the Dakota from the Niobrara. This may indicate an overlap condition, or an interval of erosion before the deposition of the Niobrara, but in neither case does it suggest quiet conditions in a slowly subsiding sea bottom far from land.

Mr. Aurand, of the Midwest Refining Company, in 1924 noticed puzzling discrepancies in the thickness of the lower Cretaceous between several measured sections and well logs in the Loveland Quadrangle. This led to a careful study of the area, including measurement of many detailed sections, and a comparison of these sections with all available well logs. This showed that on the western side of the Berthoud structure there is a considerably thicker section than on the top. The difference amounts to about 600 feet for the entire Cretaceous section, most of this difference being in the Benton and Niobrara. Differences in thickness between measured sections of the "Dakota group" and like sections in the well drilled on the top of the Berthoud structure showed a decided thinning of this section in the well. Sections were measured on Little Thompson Creek, south of the Berthoud structure, and on the Big Thompson, north of the structure. No folding exists immediately east of the old shore line at either of these points. On Fossil Creek a third section was measured, approximately 20 miles north of the Berthoud structure. Here the former shore line extends almost due north and south without any impeding structural barriers lying east of it. This section involved the same sediments as were found in the Berthoud well and in the sections measured on the Little and Big Thompson creeks. All these sections and the log of the well showed almost the same thicknesses. Sections measured on the west side of the Berthoud Structure showed greatly increased thicknesses. Sections measured on the west side of the Fort Collins, Douglas Lake, and Wellington structures also showed

[1] W. H. Cross, *U. S. Geol. Survey Geologic Folio* 7 (1894), pp. 2 and 4.

increased thicknesses on the west sides of the folds as compared with thicknesses found in wells drilled in the structure, the differences in thicknesses occurring in the Dakota, Benton, Niobrara, and Lower Pierre.

According to the writers' interpretations, these structures were in existence during early Cretaceous time. They projected up to approximately the general level of the ocean and were rising slowly throughout Dakota and Benton and into Niobrara time. Sediments carried into the sea from the land masses on the west must have struck these barriers, with the result that much more material was deposited on the western side than on the eastern. It seems probable that these barriers were submerged or nearly submerged during most of that time, but they rose sufficiently high to divert the ocean currents, or at least to check their velocities. Part of the time their tops seem to have been approximately at the plane of equilibrium, where, though the waters were free to pass over them, there was almost no erosion or deposition, though deposition was taking place around the sides. This condition seems to have persisted until Niobrara time. After that, regional submergence became greater and most of the Pierre was deposited uniformly over the top of the structures. These became buried ridges and seem to have exerted little influence on deposition until they were rejuvenated by Tertiary diastrophism.

In confirmation of this idea, magnetometer "highs" have been found to exist over these structures, as has previously been described by John H. Wilson.[1]

Also T. S. Lovering, of the U. S. Geological Survey, in a recent paper[2] presents evidence showing that the Front Range area existed as a land mass throughout much of geologic time, and in the areas where he has done detailed work (on the western side) submergence was not complete until long after the beginning of Cretaceous time.

Evidence at hand suggests that similar conditions may have existed in connection with a number of other structures in eastern Colorado. The writers hope in the near future to have considerable additional stratigraphic and geophysical information on these other areas, but the information already available strongly suggests that the present geologic structures originated or at least had been forecast much earlier and were in existence in early Cretaceous time, when they seem to have

[1] Personal communication, and paper presented before Southwestern Section A. A. A. S., April, 1929, at Albuquerque, New Mexico.

[2] "Geologic History of the Front Range." Presented before the Colorado Scientific Society, January, 1929, to be published by the Society in May, 1929.

played a part in the geography of Colorado and exerted an effect on deposition during Benton time.

J. HARLAN JOHNSON[1] and HARRY A. AURAND[2]

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GOLDEN, COLORADO

[2]MIDWEST REFINING COMPANY
DENVER, COLORADO

STUDY OF THE CROOKED HOLE PROBLEM

On April 16, 1929, the suggestion was made to Alex W. McCoy, chairman of the Research Committee of the A. A. P. G., that our Association might be of considerable assistance to the petroleum industry if, through our Research Committee, we should make an intensive study of the problem of crooked holes. Mr. McCoy approved of the suggestion, appointing F. H. Lahee as chairman of a subcommittee of the A. A. P. G. Research Committee, this subcommittee to be designated the Committee on the Study of the Crooked Hole Problem. The personnel of this committee is now in process of selection. As soon as its members have all been chosen, their names will be published. In the meanwhile we are presenting this as a preliminary announcement.

In a vote taken by the Division of Development and Production Engineering, of the American Petroleum Institute, the crooked hole problem was selected as the most important problem for investigation by its Drilling Practice Committee. The Drilling Practice Committee proposes to issue a questionnaire to be distributed in different parts of the country for the purpose of more closely defining and more intensively studying the mechanical aspects, financial losses, et cetera, of the crooked hole problem. This questionnaire barely touches on the geological aspects.

Our committee plans to treat more especially the geological aspects of the problem. There is bound to be a little duplication of effort, and this we should prefer to avoid for the sake of better efficiency in compiling results; yet we do not fear that a moderate amount of duplication will be harmful, for what we all want is a solution to the problem. Therefore, the more facts we gather, the more quickly shall we attain our object. For our guidance in this investigation the questionnaire which follows has been prepared.

We wish to emphasize here, as in the questionnaire, that private information will be carefully guarded, and that no confidential data will be published without permission from the source.

OUTLINE FOR THE STUDY OF THE CROOKED HOLE PROBLEM WITH PARTICULAR REFERENCE TO THE GEOLOGICAL ASPECTS[1]

Introductory:

That holes drilled for oil may deviate from their intended vertical course is a well known fact. The problems of how to measure, how to correct, and how to prevent such deviation, are now receiving the earnest study of a great many persons engaged in the oil business. To the end that we may gather data in the most effective way for the solution of these phases of the crooked hole problem, the accompanying questionnaire has been prepared.

In many cases the answers to this questionnaire require a record of the conditions encountered during the drilling of a well. We urge careful watching of the behavior of drilling wells and the recording of abnormal features so that these may be checked up then or later with the measured angles of the hole, if opportunity offers. In making these observations, a record should be kept, during the drilling, of the kind of bits used; size of drill stem; assemblage of parts of the drill stem; size of the hole drilled; depth of the hole; weight of the mud used; pressure used on the bit; speed of rotation; rate of circulation; ease of drilling; ease of running in and coming out with the drill stem; ease of setting the casing, et cetera. If records of this kind are kept, we shall be able to gather together a very valuable body of data which will assist us toward a rational understanding of the many phases of the crooked hole problem. It is not our intention to publish private information. All names of wells or companies will be treated as confidential. Following is the questionnaire:

A. Observations on Drilling Operations:

Although this heading is not strictly geological, it is so important that we think it advisable for geologists to assist in collecting facts and making observations along this line. Most of the data under this head will be collected under the auspices of the A. P. I.

[1]This outline was prepared by F. H. Lahee, chairman of the Committee for the Study of the Crooked Hole Problem. This committee is functioning as a subcommittee of the Research Committee of the American Association of Petroleum Geologists. Additional copies may be obtained from members of this subcommittee, the personnel of which will be announced in the *Bulletin* of the A. A. P. G., or from the chairman.

1. In drilling, notice and record variations in behavior of tools, and compare these variations with course of hole as subsequently surveyed.

2. To what extent are holes "jetted" down by the hydraulic action of the mud coming out of the bit?

3. Secure actual figures on the ratio of outlet and inlet pressures of mud circulation at bit and in swivel, respectively. (Compare total area of bit outlet channels with total area of inlet channels.)

B. Instruments or Methods of Measurement:

Various devices have been tested or used for measuring the amount and direction of deviation of crooked holes from the vertical. These instruments involve several principles, such as the magnetic compass needle; a drill stem oriented by surveying at the surface of the ground; the gyroscopic compass; the Wheatstone bridge; the inertia of a rotating mass, et cetera. For the benefit of the industry we should do what we can to compare and evaluate these different methods and instruments. We therefore recommend that, where measurements are made of the deviation of holes, the following questions be answered.

1. In making the measurements, what principle or method was involved?

2. Were the results satisfactory?

3. If not, in what respects were they not satisfactory?

4. Were any check readings made to determine the reliability of the instrument or the method?

5. What kind of check was made?

6. Have you any reliable way of proving that the method of checking was correct?

7. Has the instrument been used to survey each of two intersecting holes? If so, do the results show interference at the correct position?

8. What conditions tend to limit the use of the instrument or method, such as depth of hole; necessity for continuous circulation; effect of casing; required length of time for running in, making observations, and coming out; continuity or discontinuity of record; temperature in hole; pressure in hole, et cetera.

9. Are there dangers of loss of instrument, or loss of hole, due to some of these limitations?

10. Record any other observations or suggestions referring to instruments or methods of surveying the course of holes.

C. Studies of the Course of the Hole:

1. Keep a careful record of the conditions attending any straight (vertical) holes. It is important that we learn under what conditions holes are drilled vertically.

2. a. If the hole deviates from the vertical, at what depth does such deviation begin?

b. Does it begin very gradually, or rather abruptly?

c. In a given field, do you find that a majority of the crooked holes begin to turn away from the vertical at approximately the same depth, or within a limited range of depth? If so, what is this depth, or range of depth?

d. Can you correlate this depth or range of depth with certain drilling conditions, such as weight applied on bit; or with certain geological conditions, such as a change from a hard to a soft formation, or vice versa?

3. a. In how many holes do you find that the deviation from the vertical is in a direction *up* the dip of the strata? in how many *down* the dip of the strata? and in how many in no definite direction in relation to the dip of the strata?

b. In each case, what is the approximate amount of dip of the strata?

c. Are the formations, which were penetrated in the drilling, of fairly uniform hardness, or do they consist of alternate hard and soft layers?

d. Do you find that where the strata have a low dip there is a tendency for the hole to migrate up-dip, and where they have a high dip, there is a tendency for the hole to migrate down-dip? or do you find no such tendency?

4. a. When the course of the hole is plotted in vertical projection, that is, so that only its deviation from a vertical line can be seen, does it reveal a more or less uniformly increasing angle of deviation? or does it show any tendency to straighten up again and return to the vertical?

b. Does it show any abrupt changes in vertical angle?

c. Can you correlate the features observed in its course with definite formations? or with faults or surfaces of unconformity? or with local irregularities, such as boulders, concretions, caverns, fissures, cavey formations, et cetera? (Be careful to distinguish from mechanical causes such as fishing jobs, sidetracking, et cetera.)

5. a. When the course of the hole is plotted in horizontal projection, as if you were looking down on it from above, does it reveal a tendency to spiral?

b. If so, in what direction?

c. Is the course closed or open, that is, does it tend to return to the starting point, or does the bottom of the hole migrate farther and farther from a point vertically below its mouth?

d. If the latter, what is the ratio of the straight horizontal distance to the curving or irregular horizontal course (drift) of the hole, measured in each case in a horizontal plane from the mouth to the bottom?

e. Give actual figures for the horizontal migration.

f. Does the horizontally projected course show any abrupt changes in direction?

g. If so, can these be correlated with passage through definite geological formations, or structural conditions, such as faults, contacts, et cetera, or with such local features as boulders, concretions, caverns, fissures, et cetera? (Be careful to discriminate between these features and mechanical causes such as fishing jobs, side-tracking, et cetera.)

6. a. On a given structure, or in a given field, are the holes conspicuously more crooked in one part of the field than another?

b. Is there any relation between the structure and the distribution of crooked holes, or in the degree of crookedness of the holes?

7. Assemble all possible data for comparing subsurface contour maps based on figures obtained from holes as ordinarily drilled (that is, some straight and some crooked, and crooked in various degrees and directions) with maps based on all holes being vertical in the same districts.

8. Collect all possible data bearing on the relation of oil or gas production to the crookedness of holes. Can you describe instances of wells which, because of their deviation from the vertical and the consequent displacement of their lower parts from beneath their mouths, produced oil where they should have produced gas, or vice versa? or were small oil wells where they should have been large producers, or vice versa? or were dry where they should have yielded oil, or vice versa? et cetera.

D. Effects of Well Spacing:

All estimates and theories based on well spacing have been made on the assumption that the holes were vertical. This is usually not so.

We should find out to what degree the spacing varies at selected depths where calculations are to be made, and we should clearly mark out the lines of investigation which, for correct interpretation of their results, require a knowledge of the true position of the holes. Such lines of investigation include studies of

1. The movement of oil, water, or gas through the reservoir rock
2. The movement of fluids into the well
3. The mutual effects on yield in the case of offset wells
4. Water encroachment
5. Decline of production
6. Pressure variations
7. Re-pressuring of oil wells

Describe the effects of surveyed crooked holes on these or other similar problems.

E. Necessity for Oriented Cores:

Wherever formations have dips too steep for mapping by correlation of a key horizon, and wherever drilling is being undertaken on or in association with such structures as salt domes, faults, et cetera, it is often very necessary to know the direction of dip of steeply inclined strata encountered in the hole. By such knowledge, it is possible to determine in what direction to drill on higher parts of the structure.

In this connection, collect all possible data showing the necessity for securing oriented cores, that is, for determining the original correct position of the cores in the hole before these cores were cut.

F. Temperature Data:

1. Were records made of temperature in the hole before running the instrument for measuring the inclination of the hole?

2. To what extent do you think that temperature records have been incorrect due to the assumption that the holes in which these records were obtained were vertical when, actually, these holes were inclined and were therefore not as deep as was supposed?

3. Can you cite specific instances of temperature readings in crooked holes?

4. Can you give figures on angle and direction of deviation and also recorded temperature readings?

G. Financial Loss:

Secure all possible facts on actual money losses which can be directly or indirectly charged to crookedness of holes. This is a very

important kind of information which should be carefully and extensively analyzed.

Due to the deviation of holes from the vertical, a length of hole is often drilled in excess of the amount which would be necessary to reach the pay sand if the hole had been vertical. Give figures for actual examples. In these cases, what was the cost and therefore the loss of money per foot? Analyze these costs and losses.

H. Other Items:

If you think of any other aspects of this problem, not included under headings *A* to *G*, describe and discuss them here.

F. H. LAHEE

DISCOVERY OF OIL IN OURAL-VOLGA PERMIAN BASIN, PERM PROVINCE, RUSSIA

In the fall of 1928 the Russian Government began deep drilling near the city of Perm, primarily for potassium salts. On May 14 the first test, located 30 miles east-northeast of Perm, encountered gas and oil in commercial quanitites. The log of the well follows:

Depth in Feet	
36	Alluvium
525	Marls and gypsum, with very few potassium salt beds. Gypsum content increasing with depth
1,070	Massive gypsum, grading into anhydrite. Toward the base anhydrite interstratified with black bituminous shales
1,080	Same, indicating gas pockets aud small oil saturation in samples
	Dark gray cherty limestone. Heavy oil slopping over and very strong gas flow. On May 14 the well made one flow of 15 barrels and is now shut in. Tentative paleontological examination places this limestone in Upper Carboniferous (Pennsylvanian)

The economic importance of the discovery is of inestimable value. It opens for drilling an area 1,200 miles long and 400 miles wide, located west of the Oural Mountains, as indicated on the map. The whole Oural-Volga basin is within easy reach of Volga and Kama rivers, the main navigable arteries of central Russia.

Geologically the area much resembles the Permian basin of West Texas. The cherty limestone reported in the Perm test probably represents a major unconformity, similar to that encountered near the top of the "Big lime." The extent of the Perm area is very large; it

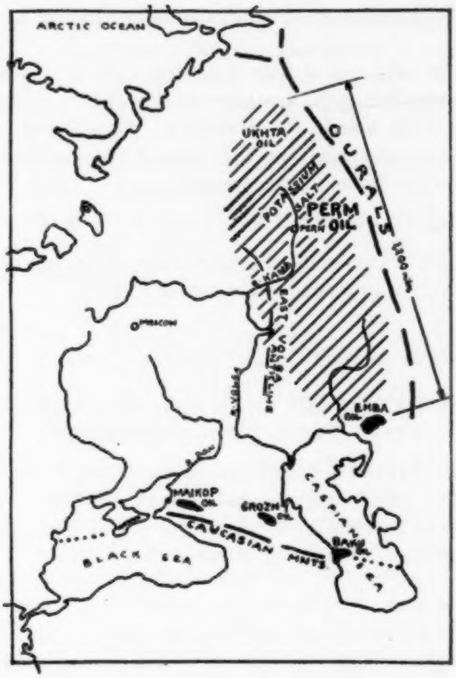

FIG. 1.—Sketch showing new potential oil area of Oural-Volga basin.

represents the remnant of the vast sea which once connected the Arctic Ocean and the Caspian Sea.

It is interesting to note that the existence of a similar inland sea in late geological times is indicated by the presence of arctic seals in the Caspian Sea of to-day, but not in the Black Sea of the Mediterranean system.

Five new tests are being planned to commence this summer, so that by winter of this year the real economic value of the new discovery will be more clearly defined. The production in the Oural-Volga Permian basin may be obtained from the basal Permian, from the Carboniferous, and from the Devonian formations. The Oural-Volga basin may eventually prove to be the richest petroleum province in the world.

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REVIEWS AND NEW PUBLICATIONS

Analytical Principles of the Production of Oil, Gas, and Water from Wells. By STANLEY C. HEROLD. *Stanford University Press* (Stanford University, California, 1928). 659 pp., 209 figs. Price, $7.50.

This book by Mr. Herold, who is a member of the faculty of Stanford University, well deserves the name of treatise and is a thoroughgoing analysis of the production of petroleum from a purely scientific standpoint. After a preliminary discussion of the laws of the physics, mechanics and thermodynamics involved, the author takes up the main body of his discussion.

He classifies reservoirs under three heads: reservoirs in hydraulic control, in which pressure and rate of production remain constant; reservoirs in volumetric control, in which pressure and rate of production decline and approach zero; and reservoirs in capillary control, in which pressure and rate of production also decline. There are two paths of decline in the last two types of control, and in order to forecast the future performance of wells and to know present conditions of recovery, it is important to be able to distinguish between these paths. The characteristics of these two types of performance the author calls primary functions. They are pressure, which determines whether or not a reservoir will produce; velocity, another name for rate of production; volume, the total amount of fluid produced or to be produced; acceleration, which is the change in rate of production; energy, which is related to the amount of gas accompanying the oil within the reservoir; power, the rate at which energy leaves the reservoir; and time, which may be either time elapsed or time remaining.

The secondary functions, as he classes them, which are events and conditions obtaining in the reservoir, are: fluids produced, sources of energy, conservation of energy, radius and area of drainage, encroachment of water on pool and well, fitness of reservoir formation for the storage of gas and oil, percentage recovery by natural flow, and fitness of reservoir for re-pressuring or for drive by water, air, or gas. These secondary functions are so called because they are identified by means of primary functions, and not because they are less important. Mr. Herold has also taken into consideration other features encountered in the field, such as "pressure gradients within the reservoir, and the effect of viscosity surface tension, and capillarity within the reservoir."

He discusses each type of reservoir with regard to these functions, establishes general principles on the basis of ideal performance, studies the effects of changes in accordance with theoretical performance, and thus reaches an understanding of actual performance as known in the field. With the knowledge so obtained, it is possible to regulate the performance of a well to the best advantage, to "know the proper back pressure to be applied, the most desirable rate of production, the most economical gas-oil ratio,. . . . and the most desirable rate for pumping."

Throughout the book the author makes liberal and very notable use of curves; for instance, he establishes a simple means of differentiating between volumetric and capillary control by the relative positions of the pressure and rate of production curves when plotted against time. He also discusses the use of curves on logarithmic paper, a matter little known but very useful to the petroleum engineer.

The book, in short, although one which I am sure very few people will be able to read as a whole, yet contains an impressive amount of information not only for the student of production, but also for the average producer who wishes to become informed concerning the scientific explanation of well behavior as he has observed it. Some of its conclusions are far in advance of present-day beliefs, but, in general, increasing familiarity with them breeds an impression of their profound importance.

R. C. BECKSTROM

TULSA, OKLAHOMA
May 17, 1929

"Bearing of Base Exchange on the Genesis of Petroleum." By E. MCKENZIE TAYLOR, School of Agriculture, Cambridge. *Journal of the Institution of Petroleum Technologists* (London), Vol. 14, No. 71 (December, 1928), pp. 825-40. 1 fig.

Geologists welcome the efforts of other sciences to aid in solving the many unsolved fundamental problems of geology. Much knowledge of geological history may be gained by a study of present processes. In view of these facts, the studies described by the author, a student of agriculture, are indeed interesting.

The phenomenon of base exchange between soils and solutions of neutral salts, studied in connection with agriculture, has led to investigations of the properties of clays. The results of these investigations find application wherever strata containing clay have been deposited under marine or estuarine conditions, since, under such conditions, the clay in the sediment is brought in contact with a solution of sodium chloride. As the deposition of sediments under marine or estuarine conditions has been taking place throughout geologic time, base exchange is a phenomenon associated with strata of all geologic ages.

From the geologic point of view, calcium clay and sodium clay are the most important, as they are characteristic of fresh water and marine conditions respectively. If calcium clay is treated with a solution of sodium chloride, base exchange will take place, and the reaction may be represented by the following equation:

$$Ca_n - Clay + 2n\ NaCl = Na_{2n} - Clay + n\ CaCl_2$$

Thus, where a silt containing calcium clay is carried in suspension and deposited in water containing $NaCl$, the sediment will contain sodium clay as a characteristic constituent. The submergence of strata in sea water or the capillary rise of salt water from a subsoil water table may also produce sodium clays.

If a sodium clay is treated with a solution of sodium chloride, the clay remains permeable, the particles being flocculated. If the sodium clay is treated with pure water, the particles are deflocculated, the water becomes alkaline, and the clay becomes impermeable. The action of pure water on sodium clay may be represented by the following equation:

$$Na_{2n} - Clay + 2nH{\cdot}OH = 2nNaOH + H_{2n} - Clay$$

Such hydrolysis of the sodium clay results in hydrogen clay and an alkaline solution. Alkaline solutions are known to be conducive to the growth of bacteria, for in such a medium their growth is not inhibited by their own toxic products, which are acidic in nature.

The properties of sodium clay may be summarized as follows. (1) Sodium clay is stable in the presence of excess $NaCl$; (2) sodium clay can be hydrolized in the presence of fresh water and as a result yields an alkaline solution; (3) if the equilibrium between ions in the unhydrolized clay and the ions of the solution is disturbed, further hydrolysis will take place until equilibrium is again established. The presence of sodium clay therefore provides a method by which the continuous alkalinity of a medium may be maintained and the toxic acidic products of bacterial action neutralized; (4) strata in which hydrolized sodium clay is present are permeable. Conditions either in or under such strata are anaerobic. The residues of bacterial decomposition in or under such strata must therefore be reduction products; (5) the impermeability of strata containing hydrolized sodium clay results in the sealing in of material under such strata.

The properties of calcium clay differ considerably from those of sodium clay. Calcium clay hydrolizes much more slowly and the alkalinity produced, calcium hydroxide, is much weaker than sodium hydroxide. Experiments have shown that hydrolysis of calcium clay does not take place sufficiently rapidly to maintain the alkalinity of a medium in which a bacterial decomposition is taking place. Calcium clay is also flocculated in fresh water and is therefore permeable to both water and gases.

From this discussion, it will be seen that if a silt is carried in fresh water and deposited under marine conditions, base exchange will take place and sodium clay will be formed. If subsequently the sodium clay is brought into contact with fresh water, it will become alkaline and impermeable as a result of hydrolysis.

If the shales overlying petroliferous sediments have undergone base exchange and subsequent hydrolysis in fresh water, they should show evidence of it in their alkalinity and in the nature of the replaceable bases which they contain. Several shales from cap rocks or near the oil zone in the Rumanian fields and from the West Indies were tested in the laboratory. These tests were significant, since without exception they were alkaline, with replaceable sodium predominating over replaceable calcium.

The methods for the examinations of the shales included: (1) the determination of the pH value of a suspension in water, and (2) the determination of the replaceable calcium and sodium. The specimens examined had an average pH value of 9.3. The replaceable calcium averaged 3.8 milligram equivalents per 100 grams and the replaceable sodium 20.8 milligram equivalents per

100 grams. This indicates that the shales were alkaline and that the sodium is markedly higher than the calcium.

It is too early to say that all shales overlying oil strata are alkaline, but it may be safely said that they have all undergone base exchange. In order that alkalinity and impermeability may develop, the sodium chloride must be leached away by fresh water. If shales are found to be alkaline, it is certain that leaching and hydrolysis have taken place.

With regard to the effect of sodium clay on the genesis of petroleum, the experiments led to the following conclusions: (a) continuous bacterial decomposition of organic matter could take place under a sodium clay roof; (b) the roof was impermeable, so that the gas accumulated under pressure; and (c) the absorption of carbon dioxide takes place through the action of the sodium hydroxide, leaving a residue of practically pure methane.

A series of organic compounds such as glycerol, cod liver oil, stearin, stearic acid, palmitic acid, et cetera, were subjected to bacterial decomposition under a sodium clay roof. The results of these tests can not be given as final, as the decomposition is still proceeding. Observations indicate that oils and fats can be decomposed under these conditions, also that a naturally occurring mixture of oils and fats decomposes in a manner similar to the pure substances. The natural oils and fats can be regarded as mixtures of the triglycerides. Therefore, if these mixtures are decomposed as suggested, it might be expected that the one constant product, methane, would be formed as glycerol in a common constituent of all glycerides. The residue after decomposition of the glycerol should be a mixture of fatty acids. The decomposition of this mixture under alkaline anaerobic conditions should result in a mixture of the corresponding paraffins. This method affords a reasonable explanation of the various constituents of petroleum and the omnipresent methane. Further investigations are being conducted.

Literature concerning the formation of petroleum from natural fats by the action of bacteria is somewhat voluminous. The bearing of base exchange, as suggested by the author, is a new application of this process. It is this application which merits some criticism.

That base exchange does take place in natural clays has long been an accepted fact. However, leaching and hydrolysis of clays on a large scale in nature do not appear logical in normal sedimentation processes. Clays are all relatively impermeable, and acidic clays, which are very common, are just as impermeable as alkaline clays. If the permeability of a surface clay was sufficient to permit downward leaching by fresh water, oil compounds generating under such clay could also be oxidized and destroyed as petroleum. Caustic alkaline solutions produced by the leaching of sodium clay would be unstable in the presence of alkaline earths and silica present. Such caustic solutions are not necessary to the existence of micro-organisms. Basic rocks, such as limestone, should be all that is necessary to neutralize the acidic products resulting from bacterial life processes.

L. C. Case

Tulsa, Oklahoma
May 24, 1929

"Zur Geologie und Mineralogie von Kolumbien (Süd-America)" (On the Geology and Mineralogy of Colombia, South America). By OTTO STUTZER. *Neues Jahrbuch* (Stuttgart, 1924-28).

These contributions give the results of recent investigations by German geologists in Colombia. Stutzer has been geologist for the Colombian Government since 1920. He has also included three articles of his predecessor, R. Scheibe, whose work, because of his untimely death, was largely unpublished or published in reports of the Colombian Government where it is practically inaccessible.

The articles were published individually in the *Neues Jahrbuch für Geologie, Mineralogie, et cetera*. As they have no continuity they may be best reviewed separately.[1]

1. "Ein Überblick über Oberflachengestalt, Geologie und Mineralogie Kolumbiens" (Review of the Physiography, Geology, and Mineralogy of Colombia). By OTTO STUTZER. *Neues Jahrbuch, 52* Abt. B (1924). pp. 162-74.

A short review of the topography, stratigraphy, tectonics, and economic geology of Columbia. A valuable bibliography is included.

2. "Das Salzvorkommen von Nemocón" (The Salt Occurrence of Nemocón). By R. SCHEIBE, 1922. *Neues Jahrbuch*, 53, Abt. B (1925), pp. 315-20.

Discusses salt occurrences at Nemocón, which is on the Bogotá plateau north of Bogotá. Hills of rock salt occur in the Lower Cretaceous Villeta group which is upfaulted among the Upper Cretaceous Guadalupe and Eocene Guaduas beds.

3. "Das Smaragdvorkommen von Nemocón" (the Nemocón Emeralds). by R. SCHEIBE, 1922. *Neues Jahrbuck*, 53, Abt. B (1925), pp. 321-24.

4. "Die Smaragdlagerstätte von Muzo (Kolumbien) und ihre nähere Umgebung" (The Emerald Deposits of the Muzo Region). By R. SCHEIBE. *Neues Jahrbuch*, Abt. B (1926), pp. 419-48.

5. "Über Spuren einer diluvial Vereisung im Gebirge bei Bogotá, Kolumbien" (Traces of Pleistocene Glaciation in the Mountains near Bogotá, Columbia). By OTTO STUTZER. *Neues Jahrbuch*, 55, Abt. B (1926), pp. 518-23.

6. "Geologische Beobachtungen und Gedanken bei ein zweimaliger Durchquering der Kolumbienischen Mittle-Kordillere" (Geologic Notes and Opinions on a Double Crossing of the Colombian Central Cordillera). OTTO STUTZER. *Neues Jahrbuch*, 56, Abt. B (1926), pp. 135-51.

The results of a trip across the Central Cordillera and a return trip by another route. Both crossings were in the general latitude of Bogotá.

The core of this cordillera consists of granites. On the flanks metamorphics occur with granitic intrusions of undetermined age. Two volcanoes emitted

[1]Those who have followed Stutzer's articles in the *Neues Jahrbuch* welcomed the listing of this book in the catalogues of the German book dealers. One naturally expected a coördinated summary of Stutzer's studies. After paying more than eleven dollars for the publication, the receipt of an envelope of reprints of these articles is disappointing.

thick and extensive lava flows in late Pleistocene or post-Pleistocene time and locally these cover the older rocks. Tuffs and agglomerates are widespread and conceal the underlying rocks in a large part of the area. The Magdalena graben bounds this cordillera on the east, and on the west it is bordered by the Cauca graben. Cretaceous rocks are absent from the east flank for a distance of 350 kilometers. Local diatomaceous deposits are numerous even at high altitudes.

7. Zur Geologie der kolumbienischen West-Cordillere zwischen Cali und Buenaventura" (Geology of the Colombian West Cordillera between Cali and Buenaventura). By O. STUTZER. *Neues Jahrbuch*, 56, Abt. B (1926), pp. 162-60.

On the western slope the young coastal plain deposits, of undetermined age, consist of flat-lying shales and plastic blue clays. The rocks of the Western Cordillera are mainly basic intrusives — diorite, diabase, gabbro, and serpentine — and older metamorphics. Oligocene limestone and sandstone occur on the east slope. The Cauca graben limits the cordillera on the east. Before this graben was formed the Western and Central cordilleras were continuous.

8. "Bemerkungen über Geologie, Oel, und Wasser im Department Atlantico in Kolumbien" (Remarks Upon the Geology, Oil, and Water in the Department of Atlantico in Colombia). By O. STUTZER. *Neues Jahrbuch*, 56, Abt. B (1926), pp. 230-42.

A north-south-trending range crosses the department and attains elevations of 400 meters. The coast line is changing in this part of Colombia because of marine erosion and deposition.

Marine Oligocene, Miocene, and Pliocene sediments are found at the surface. They consist of clays, sands, sandstone, and coral limestones. The clays form the surface throughout most of the department, causing numerous landslides and poor roads. Sandstones at Usiacuri contain andesitic material and are correlated with the upper Honda of the upper Magdalena valley. The mouth of the Magdalena was in this region at that time and not near Rio Hacha, at the edge of the Goajira Peninsula, as some have supposed.

A north-south-trending anticline extends through the entire department from Puerto Colombia. Two small anticlines occur on the west. The large anticline has been tested by several wells near Las Perdices and yielded only small amounts of oil and gas. As the oil horizons are said to contain no water, Stutzer suggests that commercial production may be encountered in the syncline on the west.

The porous coral limestone carries potable water, and Cartagena obtains its water supply from this source.

A bibliography is included with this article.

9. "Beitrage zur Geologie des Cauca-Patia Grabens" (Contribution to the Geology of the Cauca Patia). By O. STUTZER. *Neues Jahrbuch*, 57, Abt. B (1927), pp. 114-70.

The Cauca-Patia graben is a topographic and geologic depression between the Central and Western cordilleras. Its length is several hundred kilometers.

This large structural feature may be divided into the following physiographic units.

(1) The Cauca plain of Cartago-Cali. This northern unit of the graben is a level plain 200 kilometers long and 15-30 kilometers wide. Cauca River, which flows in this plain, is navigable in this part of its course, but is not navigable above and below. In comparatively recent time the plain was covered by a lake caused by subsidence of the graben at a rate more rapid than the erosion of the outlet. Diatomaceous beds formed in the lake.

On the adjacent slope of the Central Cordillera only crystallines are exposed, but on the contiguous slope of the Western Cordillera Tertiary sediments occur. Near Vijes, limestones contain fossils, probably of Oligocene age. Toward the south these grade into a coal series from which coal is mined, and which has been intruded by igneous rocks.

The Cauca plain is limited on the south by the east-west-trending Suarez-Santander range, consisting of coal series and intrusions of diorite and diabase. These are locally covered by tuffs.

(2) The Popayan plateau. This undulating plateau slopes southward from the Suarez-Santander range to the Patia valley. It is entirely covered by tuffs and gravels.

(3) The Patia valley. In this valley crystalline and Tertiary sediments occur, locally covered by volcanics and tuffs. Presumably that part of the valley formed by the graben contains no crystallines, but this point is not clear in the text.

10. "Beiträge zur Geologie der kolumbienischen Ost-Kordillere in der näheren und weiteren Umgegend von Bogotá" (Contributions to the Geology of the Colombia East Cordillera in the Immediate and General Vicinity of Bogotá). By O. STUTZER. *Neues Jahrbuch*, 57, Abt. B (1927), pp. 304-64.

The Bogotá plain is 2,600 feet above sea-level and is bordered by high mountains. In late Pleistocene time it was covered by a lake. The lake deposits consist of diatomaceous earth, peat bogs, and volcanic ash. They supply artesian water.

Evidences of glaciation were found some distance south of Bogotá. Strangely enough, none is found east of the Orinoco-Magdalena watershed. In this general region the glaciers seemingly lay west of this watershed.

About 60 kilometers east of Bogotá, in the eastern flank of the east cordillera, a limestone bed carries a brachiopod fauna of Paleozoic age, probably Carboniferous.

In the upper Magdalena valley and the Eastern Cordillera, east-west trends are not uncommon, particularly in the Tertiaries. As the trend of the cordilleras is slightly east of north, these are attributed to later disturbances. The "elbow" of the Magdalena at Girardot is caused by such a disturbance.

Near Gualanday, 20 kilometers west of Girardot, late Tertiary sediments called the Gualanday beds form a syncline. In this area, which is in the Magdalena graben, isolated hills of Cretaceous also appear. Oil seepages occur in Cretaceous (Guadalupe) beds at Guataqui. A well drilled near by encountered only traces of heavy oil. Near Honda late Tertiary sediments, called Honda beds, are locally covered by old gravels and horizontal tuffs and gravels.

11. "Zur Geologie des mittleren Magdalenentales" (Geology of the Central Magdalena Valley). By O. STUTZER. *Neues Jahrbuch*, Abt. B (1927), pp. 342-63.

This includes a discussion of the nomenclature of the Tertiary of the Magdalena valley. A new classification is advanced in which the Guaduas (Eocene) remains unchanged, but the term Honda is used to include the remainder of the Tertiary — probably Oligocene through Pliocene. The Honda is divided into two groups, a lower non-andesitic and an upper andesitic. The andesitic material came from the volcanoes of Huila, or perhaps from volcanoes still farther south. In the Sogamoso region the andesitic material does not appear in the Honda beds, indicating either that these beds are entirely lower Honda or that the andesitic material does not extend so far north.

During much of the Tertiary, a large lake comparable with the present Lake Maracaibo occupied the Magdalena valley. The waters of this lake advanced and withdrew repeatedly. The Tertiary strata were deposited in this environment.

Through much of its course the Magdalena flows in a graben which is more than 1,000 kilometers long and thousands of meters deep. North of the place where the Madgalena leaves the graben, its affluent, Rio Cesar, flows in the graben. To the north the graben terminates at an east-west disturbance which intersects the Eastern Cordillera near La Paz (Department of Magdalena).

The surface of the Eastern Cordillera consists mainly of Cretaceous strata. At the eastern border of the graben, older Tertiaries are exposed. At the western border, however, the young Tertiaries are in fault contact with, or overlap the crystallines of the Central Cordillera. Seepages occur locally along this contact.

The large seepages at Las Monas in the Sogamoso region are described. Much detailed information of structure and stratigraphy in certain localities is given. The Honda beds of the upper Magdalena valley are thoroughly described. Here a slight discordance is found between the Guaduas (Eocene) and the Cretaceous.

The oil which is found in the Honda beds is believed to have originated in the underlying Cretaceous.

12. "Zur Geologie der Goajira-Halbinsel" (Geology of the Goajira Peninsula). By O. STUTZER. *Neues Jahrbuch*, Abt. B (1928), pp. 304-26.

The pre-Cretaceous rocks, consisting of various metamorphics, effusives, and intrusives, crop out in the mountain masses and are found as float in the lowlands.

The Cretaceous consists of conglomerates, sandstones (locally tuffaceous), and blue-gray limestone. These are ordinarily found in the mountains.

Tertiary and younger marine strata rest discordantly upon older rocks. This succession is well exposed around the borders of the mountains.

The trend of the mountains is N. 65° E., but at the eastern extremity this changes through east to S. 60° E. The general trend is approximately parallel with the Merida Cordillera.

Three large fracture lines are recognized. The first trends north-south and outlines the west coast; the second trends slightly north of east and outlines

the southern coast; the third has a northwesterly trend and forms the southwestern border of the Macuire mountain mass which is in the easternmost part of the peninsula.

13. "Über erz-und gesteinmikroskopische Untersuchungen am kupferhaltigen, serpentisierten Pyroxenite von Vetica bei Santander (Caucatal) in Kolumbien" (A Microscopic Examination of Copper-bearing Serpentinized Pyroxenite from Vetica near Santander in the Cauca Valley of Colombia). By R. SCHEIBE. *Neues Jahrbuch*, 58, Abt. A (1928), pp. 141-52.

J. M. WANENMACHER

NEW YORK, N. Y.
May 31, 1929

RECENT PUBLICATIONS

ALABAMA

"Possible Salt Deposits in the Vicinity of the Jackson Fault, Alabama," by Jelks Barksdale. *Alabama Geol. Survey Circular 10* (University, 1929). 23 pp.

ARKANSAS

"Upper Cretaceous Ostracoda of Arkansas," by Merle C. Israelsky. From "Stratigraphy and Structure of the Gulf Coastal Plain of Arkansas," by W. C. Spooner and others. *Arkansas Geol. Survey Bull. 2* (Little Rock, 1929). 30 pp., 4 plates.

CROOKED HOLES

"Causes and Prevention of Crooked Holes," by A. T. Parsons. "Why Good Holes Go Wrong," by Martin Van Couvering. "How to Drill Straight Rotary Holes," by R. D. Elliott. "Drilling Straight Holes by Gravity," by H. H. Jones. *Oil Bulletin* (Los Angeles, June, 1929), pp. 587-92.

"Straight Hole Practice," by W. K. Whiteford. *Oil Weekly* (June 7, 1929), pp. 21-22, 99-101. Also see *Nat. Petrol. News* (June 5 and 12, 1929), pp. 37-41, 56-59, and *Oil and Gas Jour.* (June 6, 1929), pp. 49, 167-68, 170, 172, and 194.

"Crooked Hole Problem Minimized in Burma," by Wallace Davis. *Oil Weekly* (May 17, 1929), pp. 31-32, 1 illus.

GENERAL

"Water-Laid Volcanic Rocks of Early Upper Cretaceous Age in Southwestern Arkansas, Southeastern Oklahoma, and Northeastern Texas," by C. S. Ross, H. D. Miser, and L. W. Stephenson. *U. S. Geol. Survey Prof. Paper 154-F* (1929). Supt. of Documents, Washington, D. C. Price, $0.25.

"Algae Reefs and Oölites of the Green River Formation," by W. H. Bradley. *U. S. Geol. Surv.y Prof. Paper 154-G* (1929). Supt. of Documents, Washington, D. C. Price, $0.30.

"*Exogyra olisiponensis* Sharpe and *Exogyra costata* Say in the Cretaceous of the Western Interior," by J. B. Reeside, Jr. *U. S. Geol. Survey Prof. Paper 154-I* (1929). Supt. of Documents, Washington, D. C. Price, $0.10.

The Oil and Petroleum Year Book, 1929, by Walter E. Skinner, 15 Dowgate Hill, Cannon Street, E. C. 4, London. lix + 308 pp. The yearly record of particulars about British and foreign oil Companies, giving organization data and officers. Price 8 s. 6 d., post free.

Paleontology, by Edward W. Berry. McGraw-Hill Book Co., Inc., (New York, 1929). xii + 392 pp., 175 figs., glossary, and index. Cloth, 9¼ × 6 inches. Price, $3.50.

"Correlation of the Upper Cretaceous or Gulf Series of the Gulf Coastal Plain," by Lloyd W. Stephenson. *Amer. Jour. Sci.*, Vol. 16, No. 96 (December, 1928), pp. 485-96, Fig. 1.

"Structural Features of the Atlantic and Gulf Coastal Plain," by Lloyd W. Stephenson. *Bull. Geol. Soc. Amer.*, Vol. 39 (December, 1928), pp. 887-900, Fig. 1.

"Experiments in Connection with Salt Domes," by B. G. Escher and P. H. Kuenen. *Leidsche Geologische Mededeelingen*, Vol. 3, No. 3 (Leyden, February, 1929), pp. 132-82, plates 20-38.

"New Theories Regarding the Formation of Petroleum," by A. Weinfeld. *Inter. Zeit. für Bohrtechnik, Erdölbergbau und Geologie* (Vienna, May 1, 1929).

"Manual of Second and Third Order Triangulation and Traverse," *U. S. Coast and Geodetic Survey Spec. Pub. 145* (1929). Supt. Documents, Washington, D. C. Price, $0.60.

"The Function of Natural Gas in the Production of Oil," by H. C. Miller. *U. S. Bur. of Mines* and *Amer. Petrol. Institute Div. Dev. and Prod. Engineering.* 267 pp., 36 illus. Amer. Petrol. Institute, 250 Park Avenue, New York. Price, $2.00.

MEXICO

"Drilling Operations in Mexico Are Being Increased," by Eleuterio Martinez. *Oil Field Engineering* (Philadelphia, May, 1929), p 43, 1 map, 1 photograph.

NEVADA

"Notes on the Stratigraphy and Structure of the Northwest Portion of Spring Mountain, Nevada," by T. B. Nolan. *Amer. Jour. Sci.* (New Haven, May, 1929), pp. 461-79, 4 figs.

NEW MEXICO

"'Red Beds' and Associated Formations in New Mexico, with an Outline of the Geology of the State," by N. H. Darton. *U. S. Geol. Survey Bull. 794.* Supt. of Documents, Washington, D. C. Price, $1.30.

OKLAHOMA

"Map of Oil and Gas Fields of the State of Oklahoma." *U. S. Geol. Survey* (1929). Director of the Geological Survey, Washington, D. C. Price, $0.50.

"Age of the Folding of the Oklahoma Mountains—the Ouachita, Arbuckle, and Wichita Mountains of Oklahoma and the Llano-Burnet and Marathon Uplifts of Texas," by Sidney Powers. *Bull. Geol. Soc. Amer.*, Vol. 39 (December, 1928), pp. 1031-72, Figs. 1-11.

PERSIA AND MESOPOTAMIA

"Oil Fields of Persia and Mesopotamia," by F. G. Clapp. *Oil and Gas Jour.* (May 23, 1929), pp. 78, 204-10.

POLAND

"Neue Pionierbohrungen in den polnischen Erdölgebieten," by Karl Friedl. *Petroleum Zeit.* (Berlin, May 1, 1929), pp. 592-97, Fig. 1.

SOUTH AMERICA

"Oil Possibilities of the Eastern Andean Region of South America," by Gilbert P. Moore. *Oil Field Engineering* (June 1, 1929), pp. 20-25, 1 map, 6 photographs.

VENEZUELA

"Oil in Venezuela," by E. C. Templeton. *Oil Bulletin* (Los Angeles, May, 1929), pp. 479-81, 2 maps, 3 photographs.

WASHINGTON

"A Revision of the Flora of the Latah Formation," by E. W. Berry. *U. S. Geol. Survey Prof. Paper 154-H* (1929). Supt. of Documents, Washington, D. C. Price, $0.30.

TECHNICAL PERIODICALS

The following periodicals have been added to the list of publications regularly received at Association headquarters:

Internationale Zeitschrift für Bohrtechnik, Erdölbergbau und Geologie (Vienna)

Mitteilungen aus dem Mineralogisch-Geologischen Staatsinstitut in Hamburg (Hamburg)

For previous lists see this *Bulletin* Vol. 12, No. 8 (August, 1928), pp. 876-77; No. 10 (October, 1928), p. 1042; Vol. 13, No. 1 (January, 1929), p. 88; No. 2 (February, 1929), p. 185.

THE ASSOCIATION ROUND TABLE

LIFE MEMBERSHIP

F. A. A. Van Gogh, De Bataafsche Petr. Mij., 30 Carel van Bylandtlaan, The Hague, Holland, having fulfilled the requirements of the Constitution, has been granted life membership in the Association by the Executive Committee.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following applicants for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these applicants, please send it promptly to J. P. D. Hull, Business Manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each applicant.)

FOR ACTIVE MEMBERSHIP

G. Whitney Adams, Brownwood, Tex.
Clyde M. Becker, Allan B. Gray, G. C. Matson
E. B. Baldwin, Eastland, Tex.
E. M. Closuit, H. B. Fuqua, David Donoghue
R. C. Beckstrom, Tulsa, Okla.
C. A. Heiland, F. M. Van Tuyl, J. Harlan Johnson
Charles H. Behre, Jr., Cincinnati, Ohio
Sidney Powers, Geo. Edwin Dorsey, Albert E. Oldham
Leon Bossard, Dannevirke, New Zealand
Chester W. Washburne, W. E. Wrather, Sidney Powers
Carleton J. Cunningham, Lockhart, Tex.
George E. Burton, H. C. George, Charles N. Gould
Salvador Ortiz-Dávila, Tampico, Mexico
James W. Hunter, Carroll H. Wegemann, R. J. Spiers
Romaldo De Chicchis, Midland, Tex.
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Daniel George Emrick, Houston, Tex.
H. B. Fuqua, B. E. Thompson, Ben C. Belt
Charles B. Gauthier, Los Angeles, Calif.
Roger F. White, L. R. Van Burgh, Douglas Fyfe
L. B. Herring, Fort Worth, Tex.
D. D. Christner, H. B. Fuqua, B. E. Thompson
John T. Lonsdale, College Station, Tex.
V. E. Monnett, A. C. Trowbridge, E. H. Sellards
Eugene McDermott, Fort Worth, Tex.
H. B. Fuqua, Ben C. Belt, B. E. Thompson

Charles P. McGaha, Wichita Falls, Tex.
Willis Storm, H. B. Fuqua, B. E. Thompson
Dean A. McGee, Bartlesville, Okla.
G. S. Lambert, J. K. Knox, J. M. Sands
Gerald C. Maddox, Tulsa, Okla.
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David B. Miller, Denver, Colo.
C. W. Henderson, Dean E. Winchester, Roy Holloman
Kenneth B. Moore, Tulsa, Okla.
T. E. Weirich, A. L. Beekly, J. D. Watson
Daniel C. Nufer, Tulsa, Okla.
L. Murray Neumann, Luther H. White, Robert H. Dott
Thomas Franklin Petty, Wink, Tex.
E. H. Sellards, L. T. Barrow, H. P. Bybee
Delmer L. Powers, Edmonton, Alta., Canada
Glen M. Ruby, B. F. Hake, T. A. Link
John Clark Ross, Tulsa, Okla.
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John B. Webb, Edmonton, Alta., Canada
B. F. Hake, Glen M. Ruby, T. A. Link
Chester D. Whorton, Fort Worth, Tex.
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Henry A. Ley, Charles T. Kirk, L. E. Kennedy

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C. D. Cordry, Fort Worth, Tex.
C. L. Dake, Josiah Bridge, H. A. Buehler
Leslie A. Douglas, Norman, Okla.
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F. H. Lahee, J. A. Waters, D. M. Collingwood
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Harold Kemp, Houston, Tex.
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Wilson G. Saville, Houston, Tex.
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Kenneth A. Simmons, Evansville, Indiana
G. D. Thomas, Roscoe E. Shutt, E. G. Robinson
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Ray V. Hennen, R. J. Metcalf, Walter J. Boyle
Kathleen Tarver, Fort Worth, Tex.
N. L. Thomas, F. L. Whitney, R. A. Liddle
Randolph F. Wheless, San Antonio, Tex.
Charles H. Row, Martin Matson, Joseph M. Dawson
George E. Woodward, Jr., Oklahoma City, Okla.
C. R. Longwell, Alan M. Bateman, C. Schuchert

FOR TRANSFER TO ACTIVE MEMBERSHIP

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E. C. Edwards, Ben H. Parker, Richard T. Lyons
Joe Cannon, San Angelo, Tex.
R. L. Cannon, David Donoghue, Charles E. Yager
Norman Hardy, Los Angeles, Calif.
William S. W. Kew, E. M. Butterworth, Herschel L. Driver
Waldo W. Ports, Wichita Falls, Tex.
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L. W. Kesler, Henry A. Ley, Roy A. Burt
Reginald G. Ryan, Graham, Tex.
W. P. Haseman, Wallace C. Thompson, L. T. Patton
Michael A. Smirnoff, Houston, Tex.
A. T. Schwennesen, J. Brian Eby, John C. Myers
Everett A. Wyman, Ardmore, Okla.
Sidney Powers, Dollie Radler, F. K. Foster

RESEARCH COMMITTEE REPORT

The Research Committee of the American Association of Petroleum Geologists approves and recommends to the Executive Committee the adoption and installation of the following plan to create and maintain interest in research among Association members.

It is recommended that the Executive Committee establish a system of honors or prizes for meritorious work accomplished in petroleum geology, according to the outline herewith submitted.

I. C. White Gold Medal.—The I. C. White Gold Medal of the American Association of Petroleum Geologists shall be the highest honor conferred by the Association for distinguished contributions to petroleum geology.

Eligibility.—Any reputable person making a major contribution to the science of petroleum geology is eligible for election to the I. C. White Gold Medal of the Association. Eligibility to this honor is not restricted to membership in the Association.

Method and time of election.—Nominations shall be made by a committee composed of all the past presidents of the Association at the annual meeting of the Association. Such nominations are to be presented to the outgoing executive committee for approval and presentation of the medal.

Limitations of the award.—Not more than one award shall be made to any one individual. Not more than one award shall be made for each year of the Association's life; but in the judgment of the Nominating Committee retroactive awards may be made one for each year of the Association's past existence. Any award may be deferred from year to year provided it is the judgment of the Nominating Committee that such award is not merited at that time.

Design of the medal.—The I. C. White Gold Medal shall bear the name of the medal, the name of the individual receiving the same, the date of presentation, the insignia of the Association, and a profile engraving of I. C. White. (The design to be selected by the Executive Committee.)

One Senior Prize.—The Senior Prize shall be awarded annually to the member (active or associate) of the Association whose paper is judged to have been the best all-around contribution to oil geology published during the preceding calendar year in the *Bulletin* or other official publication of the Association — provided that holders of the I. C. White Medal, previous winners of the Senior Prize, and members of the Research Committee shall not be eligible to receive the prize.

The Research Committee suggests that the prize might suitably consist of paid-up membership in the Association for ten years.

The award of the prize shall be made by the Executive Committee but it is to be the duty of the Research Committee and the third vice-president in charge of editorial work, to nominate candidates for the prize to the Executive Committee. The suggestion is offered that some retroactive award of prizes for five past years might be desirable to set a standard for the future award of the prize.

Not more than three Junior Prizes.—The Junior Prizes shall be awarded for the best three contributions to oil geology, published during the preceding calendar year in the official publications of the Association respectively by three members (active or associate) less than 28 years of age on the first day of January of that year. Previous winners of this prize, or any member (active or associate) ineligible to receive the Senior Prize shall not be eligible for the Junior Prize.

The prize, in the opinion of the Research Committee, might suitably consist of paid-up dues in the Association for three years.

The award of the prize shall be in the same manner as the award of the Senior Prize.

The Committee expresses the opinion that joint papers in which the senior author is not eligible to receive a Junior Prize, normally should not be considered for the Junior Prize, but believes that such papers should not be formally eliminated from consideration.

It is suggested that one of the Junior Prizes might be given for the best paper describing an oil deposit and one for the best paper presenting the results of original research. It is the Committee's belief that it is most important to accumulate in the literature descriptions of the oil deposits and that a statement of fact in description of an oil deposit is a type of paper in which a junior is most likely to turn out a valuable paper.

Prizes for best geological note.—A prize shall be given for the best short note, published in the *Bulletin* during the calendar year in original description of some geologic phenomenon within the field of petroleum geology. The note should consist of approximately 1½ pages of text or less. The prize is open to members (active and associate) and to members of officially affiliated societies.

The prize shall consist of dues for one year.

The award of the prize shall be in the same manner as the other prizes.

The reason for the recommendation of this prize is the belief that members are constantly seeing in the field minor geologic phenomena, which are well worthy of being brought to the attention of other geologists and recorded permanently in the literature. Many such phenomena are referred to and buried in larger papers. The Committee believes that an attempt should be made to induce members to publish such short notes in the *Bulletin*.

Honorable Mention.—A list of names for Honorable Mention should be used in connection with the publication of the statement of the awards and should include the names of

(a) Any author who has published a paper of high merit in the official publications of the Association but who is ineligible for the Senior Prize.

(b) Any author who was less than 28 years of age on the first of January of the year under consideration, who has published a paper of high merit in the official publications of the Association but who is ineligible for the Junior Prize.

An explanatory footnote perhaps should give for each of these the reason for the Honorable Mention, for example: "On account of Mr. A.'s membership in the Research Committee, this paper is ineligible for consideration."

(c) Any authors who are eligible for the respective prizes and who publish in the official publications of the Association papers of very high merit, which, however, fail to get the prize.

Suggestions regarding Research Committee page in the Bulletin.—At the meeting of the Research Committee on March 20, there was some discussion about a page of RESEARCH NOTES in the *Bulletin*. The Committee suggests that whether or not such a page of notes be instituted, it would be advisable to make it a practice to print a list of the names and addresses of the members of the Research Committee in each issue of the *Bulletin* with some such note as the following:

"The purpose of the Research Committee is the advancement of research within the field of petroleum geology. If members working actively in research

on particular problems care to register with the Research Committee, the committee will be glad to aid them in any way it can and put them in touch with other men, who are, or have been, working on similar or allied problems and can perhaps effect some integration of the research work of the Association. If the younger, or older, members of the Association, who are doing or preparing research for publication, will come to any member of the Committee, he will be very glad to offer whatever advice, counsel, or criticism he can in regard to research, its prosecution, or its preparation for formal presentation. The Committee would be glad to have members formulate and present to it suggestions in regard to research problems and programs." (By Donald C. Barton.)

Funds for research work.—The Research Committee recommends to the Executive Committee that funds for research be raised by grants or donations (payable either in one sum or over a period of years at the option of the donor) the principal or interest of which may be used by the Research Committee for the advancement of geological research. It is suggested that such research funds carry the name of the donor. The Research Committee does not contemplate using these funds in any way to conflict with the American Petroleum Institute program. These funds are to be used only to defray traveling, drafting, and collecting expenses and no part of the funds is to be used for salaries of those working on a project.

Program and meetings for coming year.—During the last year the only definite program in progress was the Permo-Carboniferous Stratigraphic Studies of the Mid-Continent District. This work has been ably outlined and directed by R. C. Moore and F. B. Plummer. The progress of this investigation is very gratifying and the Research Committee feels that this work promises to be a creditable contribution to Association research. This project needs some financing for detail expenditures and the Research Committee recommends that the Executive Committee appropriate $500.00 to this work as soon as the Research Fund is approved.

During the coming year the Research Committee expects to review and study the literature, especially that published in the symposium on oil-field structure. The purpose of this study is to compile all available facts for particular problems concerning oil accumulation, thereby establishing the most convincing evidence for and against the various ideas and theories of accumulation. Individual chairmen have been appointed to study definite problems and report to the general committee at the next meeting, as follows:

Sidney Powers—Buried Hills as Affecting Oil Accumulation
I. A. Levorsen—Importance of Unconformities to Oil Accumulation
F. H. Lahee—Lateral *vs.* Vertical Migration of Oil
Donald C. Barton—Variation of Gravity of Oil with Depth
John L. Rich—Origin and Migration
W. T. Thom—Carbon Ratios
F. B. Plummer—Oil Source Beds

These reports are to be presented to the Committee in the form of finished papers; to be discussed by the Committee and published finally in the Association *Bulletin* with complete discussion in case the Committee considers the reports to be sufficiently complete in character; otherwise, they will be retained

in the Research Committee files for additional data and explanation. Such carry-over problems will constitute the work sheets of the Research Committee. The first series of such reports will be presented and discussed at the meeting of the Research Committee at Tulsa, Oklahoma, on August 29, 30, and 31, 1929, (headquarters: Mayo Hotel). Members of the Association are welcome to attend and the Executive Committee is especially invited to assist in these meetings. The dates of other meetings will be announced later.

ALEX W. McCOY,
Chairman, Research Committee

Members present:

DONALD C. BARTON
I. A. LEVORSEN
R. C. MOORE
W. T. THOM
W. E. Wrather
F. B. PLUMMER
F. H. LAHEE
ALEX W. McCOY

AT HOME AND ABROAD

The fifteenth annual meeting of the A. A. P. G. is to be held at New Orleans, March 20, 21, and 22, 1930.

The Sixth International Petroleum Exposition will be held at Tulsa, October 5-12, 1929. Enlarged space is being provided for scientific exhibits. An assembly hall is being built for meetings and lectures. The A. A. P. G. will have its booth as usual.

C. A. Heiland, professor of geophysics at the Colorado School of Mines, Golden, Colorado, sailed for Europe, May 16, on a combined business and pleasure trip. He will also visit scientists and institutions engaged in geophysical research. He expects to return to Golden about the middle of September.

Frank C. Adams has been appointed division geologist for the South Texas Division of The Texas Company, with headquarters at Houston, Texas.

Carl Beal has returned to Los Angeles, California, after an extended European trip.

Roderick Burnham, who is manager of lands of the Union Oil Company of California, at Los Angeles, California, has left for an extended trip to Africa, Australia, Spain, France, and England. He was accompanied by his wife and daughter, and Frederick R. Burnham, chief of the Burnham Exploration Company.

M. Wood Stanley died April 27, at Dilley, Texas.

The fifth annual field meet of the New York State Geological Association was held May 17 and 18, at Gouverneur, New York. A total of 150 geologists from ten universities and colleges and the New York State Museum were present. Edward S. C. Smith of Union College was elected president of the organization.

Daniel Franklin Higgins, a graduate of Northwestern University and lecturer in petroleum geology at that university for the second semester of 1928-29, has accepted the professorship of geology at Lincoln Memorial University, Harrogate, Tennessee, for the year 1929-30.

Gilbert P. Moore, consulting geologist, New York City, has an article on "Oil Possibilities of the Eastern Andean Region of South America," in the June 1 issue of *Oil Field Engineering*.

Luther H. White, chief geologist of the J. A. Hull Oil Company, Tulsa, Oklahoma, was elected a member of the Tulsa Board of Education, in an election held in May.

The newly organized Oklahoma City Geological Society has elected the following officers: president, Hubert E. Bale, 701 Continental Building, Oklahoma City; vice-president, A. H. Richards, of the Ramsey Petroleum Cor-

poration, Oklahoma City; and secretary-treasurer, R. W. SAWYER, of the Skelly Oil Company, Oklahoma City.

W. L. WALKER, formerly chief geologist of the Empire Companies at Bartlesville, Oklahoma, is now in California on special service for the Cities Service Oil Company, to which the Empire Companies are subsidiary.

President J. Y. SNYDER has appointed the following new members on the A. A. P. G. Research Committee, to serve for three years: SIDNEY POWERS, L. C. SNIDER, and W. C. SPOONER.

H. R. VAN GILDER, formerly with the Pan-American Transport and Fuel Company at Tampico, Mexico, has accepted a position with The Pure Oil Company. During the summer Mr. Van Gilder will work with HORACE N. CORYELL in western Oklahoma.

LLOYD NORTH is in charge of geological work on the Gulf Coast for the Continental Oil Company (Marland Oil Company).

THOMAS G. MADGWICK, of Calgary, published "The Oil and Gas Situation in the Prairie Provinces" in the *Canadian Institute of Mining and Metallurgy Bulletin 204* for April, 1929.

HUBERT BALE, of Oklahoma City, is associated with W. H. ATKINSON.

K. C. HEALD, of Pittsburgh, Pennsylvania, has returned from Venezuela.

C. MAX BAUER and family will move from Amarillo, Texas, early in September, to Boulder, Colorado, where they will make their home. Mr. Bauer was formerly with the United States Geological Survey and has been in the geological department of the Midwest Refining Company and its subsidiaries since 1921. Mr. Bauer will take graduate work in physics and geophysics at the University of Colorado during the next two years.

JOHN FRANKLIN DODGE, fuel oil engineer of the Standard Oil Company of California, has been named professor of petroleum engineering in the College of Engineering of the University of Southern California.

GLEN M. RUBEY is president of the Nordon Corporation with producing properties in the United States and Canada. C. G. WILLIS is president and managing director of an American subsidiary, the Nordon Oil Corporation of Delaware with offices in Los Angeles. R. B. MORAN, geologist of Los Angeles, is a director. BEN HAKE, another former Marland geologist, is associated with Rubey in Canada.

H. C. GEORGE, professor of petroleum engineering at the University of Oklahoma, and J. D. THOMSON, geologist and petroleum engineer, have opened an office at 704 Colcord Building, Oklahoma City. Dr. George will devote his vacations to consulting business.

KARL E. YOUNG, geologist for the Rycade Oil Corporation, Houston, Texas, resigned that position on June 1. Mr. Young expects to engage in special work at the University of California.

STANLEY JAY succeeds A. K. TYSON, geologist for The Pure Oil Company at San Antonio, Texas. Mr. Tyson is transferred to San Angelo.

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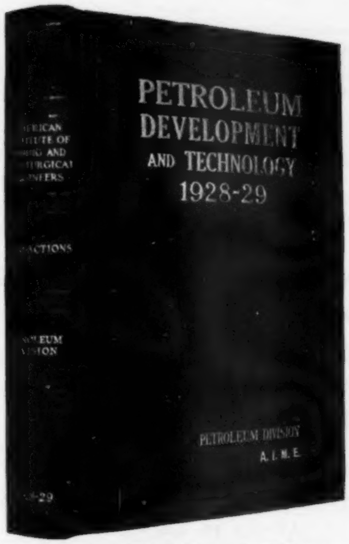

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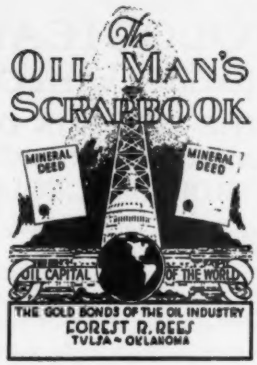

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